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Exploring Interactions in Vehicular Networks

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Exploring interactions in vehicular networks

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This thesis is dedicated to my loving family and friends who have supported me throughout my academic journey. Your encouragement and belief in my abilities have been my driving force. Thank you for always being there for me.

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> Ebenezer, “Thus far the Lord has helped us.”
>
> 1 Samuel 7:12

I thank God first, for giving me strength, and health and blessing me during this journey. God thank you for not leaving me at the moment I needed it most.

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Resumo

Nos últimos anos, as Redes Veiculares (VANETs) surgiram como uma área atraente de aplicação e pesquisa. Cada vez mais os veículos estão equipados com sensores, capacidade de processamento e recursos para comunicação sem fio, que abrem uma gama de possibilidades para aplicações destas redes no dia-a-dia dos seres humanos. Assim, as VANETs têm um grande potencial de mudar a vida de seus usuários, provendo serviços de segurança, informação, localização, entretenimento, conforto, etc. As VANETs se diferenciam das demais redes, pois seu uso pode influenciar fortemente nas decisões dos condutores, evitando a morte de muitas pessoas. Além disso, essas redes apresentam características bem peculiares como: topologia altamente dinâmica, conectividade intermitente, alta velocidade de movimentação dos veículos e grandes variações na densidade de veículos em circulação, que se tornam grandes desafios para o projeto de qualquer tipo de protocolo e serviço.

Durante suas trajetórias, por meio das interações entre veículos e as estações de acesso, os veículos podem ser comunicar uns com os outros e com outras redes. Além disso, atrevés das interações com outras entidades (sensores, dispositivos móveis), os veículos podem realizar diferentes atividades. Neste trabalho, estudamos as interações entre os veículos e as demais entidades numa VANET. Neste contexto, pretende-se entender como essas interações acontecem, a fim de prover melhor serviços e protocolos para redes veiculares. Assim, as principais contribuições deste trabalho são: primeiramente, identificamos as principais entidades de uma rede veicular e como elas podem interagir entre si. Além disso, apresentamos uma descrição dos diferentes fatores que têm um impacto sobre essas interações, e os tipos de aplicações que podem ser produzidos através delas. Em seguida, apresentamos a partir dos conceitos de redes complexas e técnicas estatísticas, uma análise detalhada de traces de veículos encontrados na literatura, com o intuito de caracterizar as interações entre os veículos. Através dessa análise foi verificado a existência de uma grande influência do comportamento do condutor e sua rotina nas interações realizadas pelos veículos. Também foi apresentado uma solução para disseminação de dados em redes veiculares ciente das interações existentes e do comportamento dos veículos. Resultados de simulação mostraram que nossa solução alcança uma alta taxa de entrega, reduzindo o atraso e o overhead na entrega das mensagens.

Palavras-chave: Redes Veiculares, Comunicação, Interações, Comportamentos, Rotinas.

Abstract

Vehicular Networks (VANETs) have emerged as an exciting research and application area. Increasingly vehicles are being equipped with embedded sensors, processing, and wireless communication capabilities, opening a myriad of possibilities for powerful and potentially life-changing applications for safety, efficiency, comfort, public collaboration, and participation while on the road. Although considered a particular case of a Mobile Ad Hoc Network, VANETS hold a vital feature - the possibility to positively influence people's life decisions. Therefore, these networks present specific features, such as highly dynamic topology and intermittent connectivity due to high-speed vehicles and high vehicle density variation. Therefore, designing any protocol and service in this scenario is challenging.

During their trajectories, using interactions among vehicles and roadside units, the vehicles can communicate with one another or with other networks. Moreover, vehicles can perform different activities when interacting with other entities (e.g., mobile devices, sensors). In this work, we study the interactions among the vehicles and the other entities in VANETs. In this context, we intend to understand how these interactions happen to promote better services and protocols for VANETs. Thus, the main contributions of this work are: firstly, we identify the main vehicular network entities and how these entities can interact among themselves. Moreover, we present a description of the different factors that impact those interactions and which application types are produced through those interactions. Then, through complex network concepts and statistical techniques, we present a detailed analysis of vehicular traces found in the literature to characterize vehicle interactions. Through this analysis, we verify that there is an excellent influence on the driver's behavior and routine in vehicular interactions. Also, we present a solution for data dissemination in vehicular networks aware of the interactions and the vehicle's behavior. Simulation results showed that our solution achieves a high delivery rate, reducing the delay and the overhead in the message delivery.

Keywords: Vehicular Networks, Interactions, Behaviors, Social Networks

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CHAPTER 1

Introduction

> "If you find a path with no obstacles, it probably doesn't lead anywhere."
>
> Frank A. Clark

1.1 Motivation

Advances in microelectronics and computer networks have enabled the creation of sensors with the ability to communicate with others via a wireless interface. These sensors commonly collect environment information and target tracking [Akyildiz et al., 2002]. Otherwise, it is possible to use these sensors in vehicles. In this scenario, sensors can be installed in vehicles to assist in braking, to alert the existence of obstacles, to collect vital driver signs, to inform above the permitted speed, and to gather environmental data such as temperature, humidity, light, and traffic conditions. Moreover, sensors can interact with vehicles and the environment, collecting data that can assist drivers in deciding on their trips. Additionally, vehicles can communicate with them to exchange information and ensure safe driving. These applications are some examples of what we can name an Intelligent Transportation System (ITS), whose goal is to improve security, efficiency, public awareness, and enjoyment in transportation systems through the use of new technologies for communication.

VANETs are comprised of vehicles with processing and wireless communication capabilities, traveling on streets or highways and sending and receiving data. These networks differ from traditional networks in many features. First is the nature of the nodes. In VANETs, the nodes can be cars, trucks, buses, and taxis, each with a different mobility pattern. All nodes exchange information among themselves and roadside units (RSUs), which connect the VANETs to the Internet or other networks. A second and essential feature of VANETs is the node's mobility. In this network, vehicles have high mobility, making the topology very dynamic [Yousefi et al., 2006; Boukerche et al., 2008; Faezipour et al., 2012].

Many are the applications in VANETs, such as driver assistance, entertainment, safety traffic, automatic parking, and group communications. For example, in driver assistance, vehicles are provided with sensors to collect drivers' conditions, weather information, roads condition, and speed limits. Thus, the vehicles can interact with the roadside infrastructure to provide real-time information to drivers. In this direction, vehicles can communicate with each other about possible dangers along the roads. Researchers show that the primary cause for most accidents is drivers' lack of attention, followed by the drivers that do not observe the safety distance among the vehicles. As the third leading cause was indicated, the high speed CESVI [2012]. Recent studies investigate the use of VANETs in this situation, and they showed that 60% of car crashes could be avoided if the driver is warned seconds before the collision. In this scenario, the interaction vehicle-vehicle broadcasts alerts to drivers, preventing accidents or traffic jams [Yang et al., 2004].

Another possible application of VANETs is entertainment, allowing drivers and passengers to access multimedia content, games, and messengers during the trips. Passengers can interact with the road infrastructure to download and upload data from the Internet. Also, the passengers can use services to look for restaurants, gas stations, hotels, etc., nearby roads and highways to support their trips. Additionally, in conurbation problems, with higher traffic flows, there are many efforts to reduce the number of vehicles in transit, mainly during rush hours. We can reach this goal by enabling the vehicle information exchange to create carpooling services.

1.2 Problem Statement

Aiming to create a vehicular network and promote communication among vehicles, it is essential to understand which entities compose a vehicular network and how these entities interact with each other. In a vehicular network, we identify vehicles, mobile devices, and smart infrastructure (RSUs, smart signs, and sensors) as examples of entities. In this scenario, an interaction can be defined as *"an occasion when two or more people or things communicate with or react to each other"* [Press, 2015], i.e., in the context of vehicular networks, interactions occur whenever there is a communication between two or more entities. For instance, when moving along the roads, vehicles may interact with the smart infrastructure, such as speed limits and direction controllers, which directly impacts road traffic. Besides, interactions among vehicles, mobile devices, and the smart infrastructure provide drivers with information such as obstacles, crashes, and traffic jams ahead, allowing them to change routes.

Many factors can impact the interactions. First, the vehicle's mobility is influenced by the speed limits and directions imposed by public roads. Furthermore, the day period may affect the vehicle's mobility. For instance, in rush hours, the traffic can be slower with a higher density of vehicles, and traffic jams can force the driver to stop or change the route. On the other hand, weekends, daily breaks, and holidays are considered quiet traffic scenarios with low vehicular density.

The driver's behavior and routine also influence the interactions. At the weekends, destinations like camping, malls, and churches are chosen for leisure and entertainment and are frequently visited. On the contrary, on weekdays, people repeat their trajectories simultaneously to the same destination, such as school, work, university, hospital, and restaurant. The density variation in different hours and days reinforces the character of the dynamic topology of VANETs, making communication a challenging task. In this context, it is likely to study driver behavior and how it impacts vehicular interactions, aiming to improve the services, communication, and protocols in VANETs.

1.3 Goals

The thesis aims to analyze interactions in vehicular networks, taking into account all the communication types presented among entities, vehicular behaviors, and city routines. In this context, it is essential to consider vehicle interactions, frequency, time, and place where they happen. Thus, we want to identify features and patterns in those interactions to exploit them and improve communication in vehicular networks. Therefore, our first specific goal is to classify all the entities and their interactions in vehicular networks. Also, we want to discuss the factors which influence the interactions and how we can explore interaction properties to promote services and protocols in VANETs.

After that, as our second specific goal, we investigate how the knowledge of those interactions can improve the performance and availability of vehicular network services. Thus, considering the traffic analysis and the features of the interactions, we propose solutions and protocols considering these properties.

1.4 Contributions

This thesis's main expected contribution is to understand the interactions in vehicular networks better, considering the routines and the driver's social aspects. In this way, we summarize the contributions below:

- **Interactions**: aiming to understand the communication in VANETs better, we present a discussion about all the entities present in VANETs, and how these entities can interact with them from a communication point of view. Also, we enumerate a group of factors that can influence these interactions. After that, we discuss using these interactions to promote applications, services, and protocols to VANETs.
- **Interactions Characterization:** We intend to present an analysis of vehicular interactions. This evaluation considers data set traces, which contain the movement's description from a group of vehicles. Thus, we create temporal graphs describing the vehicle's interactions during a period and compute metrics to attest to similar behaviors among the vehicles. Moreover, we use random graphs to increase the accuracy of this analysis and to prove some features. Aiming to perform the analysis, we will define time-space metrics that portray the driver's behavior, routines, encounter frequency and understanding of how the vehicles interact among them. We also use statistical correlation to capture proprieties and special features. This analytical study aims to find behaviors and features that can help design new solutions for vehicular networks.
- **Data Dissemination Solution:** Many are the services in the literature that can perform data dissemination in Vehicles Networks. However, these services solve the two known problems in VANETs: the *broadcast storm problem* and the *intermittently connected network problem*. Due to the high-density variation, these are significant challenges to consider in data dissemination in VANETs. Despite the excellent performance of these services, we believe that being aware of the driver's routines and the relationship with other vehicles can be a key to improving data dissemination. Thus, we propose *Socially Inspired Data Dissemination* for VANETs. In our approach, we use three social metrics, *clustering coefficient*, *node degree*, and *topological overlap* to determine when vehicles should rebroadcast data messages to increase the delivery guarantee and reduce the overall network overhead and the delay, independently of the perceived road traffic condition.

1.5 Outline

This thesis is organized as follows: Chapter 2 presents an overview of the current state of the art of applications and data communication. Chapter 3 discusses the entities and interactions presented in VANTETs. Moreover, it presents new perspectives to apply interaction in applications and communication protocols. Chapter 4 presents an interaction characterization using vehicular mobility traces, highlighting properties, features, and behaviors in VANETs. Also, it describes the modeling assumptions, the metrics, and the numerical results. Chapter 5 defines our social data dissemination solution that considers the social features of vehicles and networks. Chapter 6 presents the conclusion, future works, and publications produced by this thesis. Appendix A evaluates the impact of the initial delay in forwarding a data message during the dissemination process. Appendix B explores and quantifies the impacts of the parameters to perform the data dissemination.

CHAPTER

2

Background

“When it is obvious that the goals cannot be reached, don’t adjust the goals, adjust the action steps.”

Confucius

2.1 VANET Background

Given the advances in information technology and communication, the concept of a networked vehicle has received immense attention worldwide. A current trend is to provide vehicles and roads with capabilities to make the transportation infrastructure more secure, efficient, and urban aware and make passengers' time on the road more enjoyable. In this context, a more secure transportation infrastructure means to provide information about traffic jams, accidents, hazardous road conditions, possible detours, weather conditions, and location of facilities (e.g., gas stations and restaurants) [Chowdhury et al., 2014]; more efficient means an increased road network capacity, reduced congestion, and pollution [Chen et al., 2010], shorter and more predictable journey times, lower vehicle operating costs, more efficient logistics, improved management and control of the road network, and increased efficiency of the public transport systems [Tostes et al., 2013].

Vehicles can also be used to collect, analyze and share knowledge of an Area of Interest (AoI) [Yan et al., 2012] in applications such as civilian surveillance (photo shots of violent scenes in progress sent to public authorities via infrastructure), pollution control, roads, and traffic planning and innumerable others urban-aware applications. Finally, more enjoyable means to provide Internet access, tourist/advertising information, social media on the road, guidance for people to follow each other on the road, games, file downloads, and social applications (e.g., microblogs and chats) [Barghi et al., 2009]. These applications are typical examples of what we call an Intelligent Transportation System (ITS), whose goal is to improve safety, efficiency, urban awareness, and enjoyment in transportation systems through new technologies for information and communication.

An essential component of an ITS is the vehicular communication network (VANET) that enables information exchange among vehicles. A VANET is a particular case of a Mobile Ad Hoc Network (MANET) in which vehicles equipped with wireless and processing capabilities can create a spontaneous network while moving along roads. Direct wireless communication from vehicle to vehicle makes it possible to exchange data without communication infrastructure, such as base stations of cellular phones or access points of wireless networks.

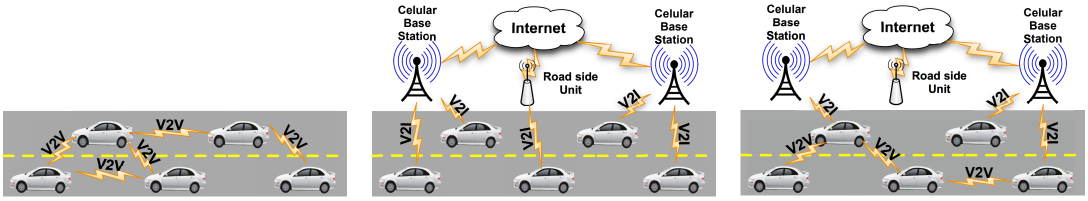
A VANET will be a significant step toward realizing intelligent transportation systems. Nowadays, many car manufacturers supply vehicles with onboard computing and wireless communication devices, in-car sensors, and navigation systems (e.g., GPS and Galileo) in preparation for deploying large-scale vehicular networks. Using different sensors (e.g., road and weather conditions, state of the vehicle, radar, and others), cameras, computing, and communication capabilities, vehicles can collect and interpret information to help the driver make a decision, particularly in driver assistance systems. In this case, there is strong support from the industry, academia, and standardization agencies to develop standards and prototypes for vehicular networks.

This chapter presents an in-depth discussion of the protocol stack in vehicular networks, including a detailed qualitative comparison of protocols from different layers. It also presents a comprehensive overview of the current state of the art of applications and data communication. The remainder of this chapter is organized as follows. Section 2.1.1 presents more characteristics of VANETs. Section 2.1.2 presents the protocol stack for VANETs. Section 2.1.3 discusses existing and future applications for vehicular networks. Finally, Section 2.2 concludes and presents future directions.

2.1.1 Features

The advances in mobile communications and the current trends in ad hoc networks allow different deployment architectures for vehicular networks in highways, urban and rural environments to support many applications with different QoS requirements. The goal of a VANET architecture is to allow communication among nearby vehicles and between vehicles and fixed roadside equipment, leading to the following three possibilities (as shown in Figure 2.1):

- *Vehicle-to-Vehicle (V2V) ad hoc network*: allows direct vehicular communication without relying on fixed infrastructure support and can be mainly employed for safety, security, and dissemination applications;
- *Vehicle-to-Infrastructure (V2I) network*: allows a vehicle to communicate with the roadside infrastructure mainly for information and data gathering applications;
- *Hybrid architecture*: combines both Vehicle-to-Vehicle (V2V) and Vehicle-to-Infrastructure (V2I). In this scenario, a vehicle can communicate with the roadside infrastructure in either single-hop or multi-hop, depending on the distance, i.e., if it can or cannot access the roadside unit directly. It enables long-distance connections to the Internet or to vehicles that are far away.



(a) Vehicle-to-Vehicle Ad Hoc Network (b) Vehicle-to-Infrastructure Network (c) Hybrid Architecture

Figure 2.1: VANET Architectures.

A VANET has some particular features despite being a special case of a MANET and presenting some similar characteristics, such as low bandwidth, short transmission range, and omnidirectional broadcast:

- *Highly dynamic topology*: a vehicular network is highly dynamic for two reasons: the vehicles' speed and radio propagation characteristics. Vehicles have high relative velocities in the order of 50 km/h in urban environments to more than 100 km/h in highways. They may also move in different directions. Thus, vehicles can join or leave the network quickly, leading to frequent and fast topology changes.

- *Frequently disconnected*: the highly dynamic topology results in frequent changes in its connectivity. Thus the link between two vehicles can quickly disappear while they are transmitting information;
- *Geographical communication*: vehicles to be reached typically depend on their location. This differs from other networks where an ID or a group ID defines the target vehicle or a group of target vehicles;
- *Constrained mobility and prediction*: VANETs present highly dynamic topology, but vehicles usually follow a specific mobility pattern constrained by roads, streets and highways, traffic lights, speed limit, traffic conditions, and drivers' driving behaviors. Thus, given the mobility pattern, the future position of the vehicle is more feasible to be predicted;
- *Propagation model*: typically, VANETs operate in three environments: highway, rural, and city. In a highway, the propagation model is usually assumed to be free space, but the signal can suffer interference by the reflection with the wall panels around the roads. A city's surroundings make communication complex due to the variable vehicle density and the presence of buildings, trees, and other objects, acting as obstacles to signal propagation. Such obstacles cause shadowing, multi-path, and fading effects. Usually, the propagation model is assumed to not be free space due to those characteristics of the communication environment. In rural environments, due to the complex topographic forms (fields, hills, climbs, dense forests, etc.), it is important to consider the signal reflection and the attenuation of the signal propagation. Therefore, in this scenario, the free-space model is not appropriate. As in any other network, the propagation model in a VANET must consider the effects of potential interference of wireless communication from other vehicles and the existence of largely deployed access points.

All these features bring new challenges to the design of communication protocols in VANETs. The spatial-temporal constraints of this type of network and the heterogeneity of vehicles in speed and mobility are design factors to be considered in developing algorithms and protocols for vehicle networks. For instance, considering cars and trucks versus buses and trams: cars and trucks have different speeds and tend to follow an unpredictable mobility model, whereas buses and trams have a regular, slower speed and a predictable mobility model.

2.1.2 Protocol stack

Considering their distinct characteristics, the protocol stack for vehicular networks has to deal with communication among nearby vehicles and between vehicles and fixed roadside equipment. Since there is no coordination or initial configuration to set up a VANET, there are several challenges in the protocol design. In the following sections, we discuss protocols for VANETs according to each layer of the network architecture.

2.1.2.1 Physical layer

Protocols for the physical layer have to consider multipath fading and Doppler frequency shifts caused by fast movements of nodes among the roadway environments. Experimental vehicle-to-vehicle communications have used radio and infrared waves [Papadimitratos et al., 2009]. Very high frequency, micro, and millimeter waves are examples of radio waves used for V2V communications. Both infrared and millimeter waves are suitable only for line-of-sight communications, whereas VHF and microwaves provide broadcast communications. In particular, VHF supports long-range links at low speeds, and because of that, the trend is to use microwaves.

Defined specifically to VANETs, the DSRC (Dedicated Short-Range Communication) system is a short to medium-range communication technology that operates in the 5.9 GHz band for the use of public safety and private applications [Kenney, 2011]. Therefore, in the United States, the Federal Communications Commission (FCC) allocated 75 MHz in the 5.850–5.925 GHz band for DSRC, in contrast to the European Telecommunications Standards Institute (ETSI), which allocated 70 MHz in the 5.855–5.925 GHz band. The DSRC system supports a vehicle speed up to 200 km/h, nominal transmission range of 300 m (up to 1000 m), and the default data rate of 6 Mbps (up to 27 Mbps).

DSRC is known as IEEE 802.11p WAVE (Wireless Access in Vehicular Environments), designed based on earlier standards for Wireless LANs [Jiang and Delgrossi, 2008]. It describes functions and services that coordinate the operation in a rapidly varying environment and exchange the message without having to join a Basic Service Set (BSS). IEEE 802.11p also defines techniques and interface functions controlled by the MAC layer. Therefore, it is limited by the scope of the IEEE 802.11 standard, which means that the physical and MAC layers work within a single logical channel. As shown in Figure 2.2, the upper layer treats the other complexities related to the DSRC channel according to the IEEE 1609 standards.

As we can see in Figure 2.3, the frequency band is divided into six service channels

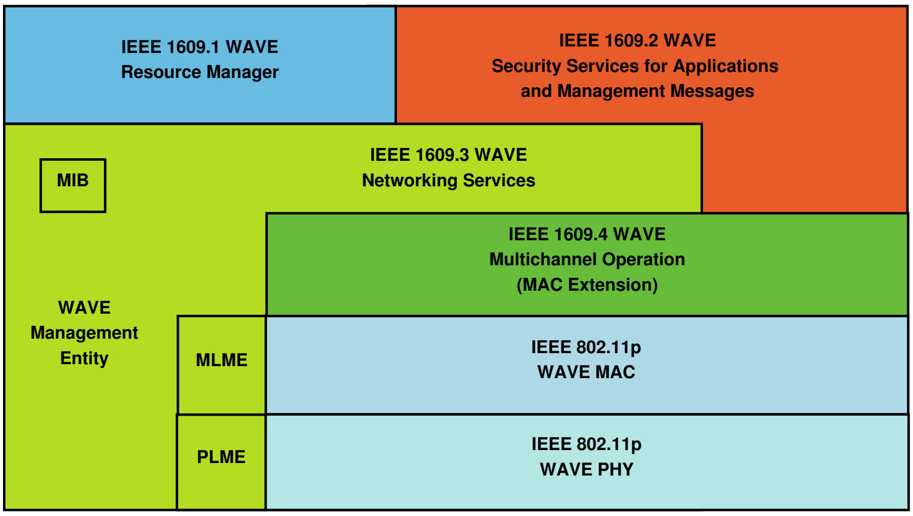


Figure 2.2: The IEEE 1609 (WAVE) reference architecture and relationship to the IEEE 802.11p MAC and physical layers [Gräfling et al., 2010].

(SCH) and one control channel (CCH) with equal bandwidth of 10 MHz each one. According to the ETSI Institute [Institute, 2013], each channel is attributed to an application type: from the range 5.855 MHz to 5.875 MHz is dedicated to ITS non-safety applications, 5.875 MHz to 5.905 Mhz is dedicated to safety and traffic efficiency applications, and 5.905 MHz to 5.925 Mhz to future applications in ITS. In DSRC, the spectrum is divided into time slots of 50 ms. Messages have two priorities: low for data dissemination messages transmitted in the SCH channels or high for safety or control messages transmitted in the CCH channel. All vehicles monitor these messages. If the CCH channel is active, all nodes are bound to stop communicating during the CCH time frame to receive and transmit security messages in the CCH channel. DSRC is proposed to support communication between vehicles and roadside units.

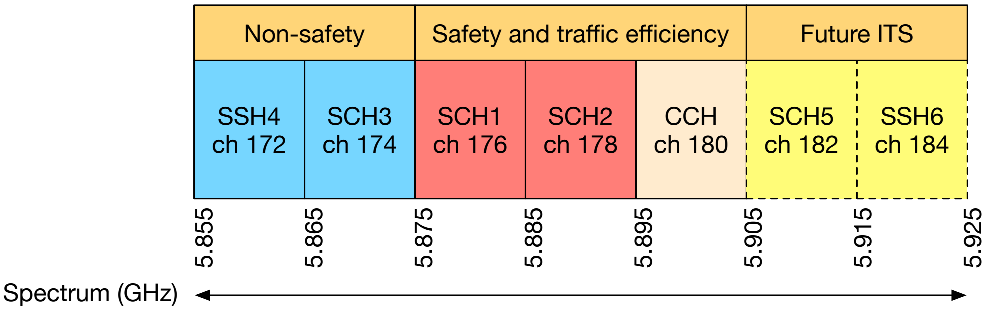


Figure 2.3: Multichannel operation in vehicular networks according to the IEEE 802.11p European standard [Festag, 2014].

Within the IEEE 802.11 technical committee, the IEEE 802.11p WAVE protocol proposes amendments to the physical (PHY) and medium access control (MAC) layers of the existing IEEE 802.11 wireless standards to support ITS applications. This includes data exchanges between high-speed vehicles and vehicles and the roadside infrastructure in the 5.9 GHz band. The ultimate goal is to have WAVE as an international standard applicable worldwide.

2.1.2.2 MAC layer

The MAC layer has to provide reliable, fair, and efficient channel access. MAC protocols should consider the different kinds of applications for which the transmission will occur. For instance, messages related to safety applications must be sent quickly and with meager failure rates. This calls for an efficient medium sharing, which is even more difficult in VANETs due to high node mobility and fast topology changes.

MAC protocols for VANETs [Almalag et al., 2013] have to deal with the hidden station problem, which frequently shows up in scenarios where vehicles form long rows, causing a decrease in the data transfer. This is especially important since there is a trend to make multimedia applications available for passengers in vehicular networks that will demand a higher data rate. Furthermore, VANET's bandwidth must be shared among the communicating vehicles. In the following, we briefly discuss the MAC protocols for VANETs found in the literature, clustering the protocols according to the medium access control mechanism.

Using OFDM technology to control the medium access and carrier sense mechanism to avoid collisions, the protocol IEEE 802.11p WAVE is designed to fulfill the requirements present in V2V and V2I communications patterns, where high reliability and low latency are critical. The key is enabling a very efficient communication group setup without much overhead, simplifying the BSS operations from IEEE 802.11 ad hoc manner for vehicle usage. For example, in the United States, the Vehicle Infrastructure Integration (VII) initiative proposed that information about an accident should be communicated through a VANET within 500 ms to all equipped vehicles in a 500 m range [Menouar et al., 2006].

Similar to the IEEE 802.11 standard, the Directional MAC (D-MAC) [Ko et al., 2000] protocol proposes two different schemes: an ACK is sent immediately after a DATA, and if a given terminal is aware of an ongoing transmission between some other two terminals, the former does not participate in a transfer itself. D-MAC scheme 1 uses directional RTS frames, and D-MAC scheme 2 uses both directional RTS and omnidirectional RTS frames. The basic principle of D-MAC is that if a directional antenna at some terminal is blocked, other directional antennas at the same terminal may not be blocked, allowing transmission using those unblocked antennas. This protocol focuses on reducing collisions and increasing channel transmission reuse.

Differently, some MAC protocols use of ALOHA approach to define the transmission schedule. ADHOC MAC [Borgonovo et al., 2004] uses the Reliable Reservation ALOHA

(RR-ALOHA) protocol, a distributed reservation protocol that creates a reliable single-hop broadcast channel, the Basic Channel (BCH). Each BCH carries signaling information to solve hidden and exposed terminal problems and efficiently implement a network broadcast service. The basic idea is to have each terminal periodically transmit the frame information (FI), i.e., the status of slots in the previous period. ADHOC MAC works independently from the physical layer, and its main disadvantage is that the medium is not used efficiently. The number of vehicles communicating in a given region is not higher than the number of time slots in the frame time.

Besides, the VC-MAC (Vehicular Cooperative Media Access Control) [Zhang et al., 2009] protocol uses the concept of cooperative communication tailored for VANETs. To maximize the system throughput, the broadcast is made by the access point based on the premise that under the information-downloading scenario, all vehicles are interested in the same information. During the transmission, due to the unreliability of the wireless channel, a group of vehicles may not receive the correct information. Then, the vehicles that received the information will be selected to relay to their neighbors. Therefore, to reduce the probability of collisions and interference, the protocol uses only a part of the vehicles to create a group of suitable relays. This protocol aims to perform excellently in broadcast scenarios, which does not consider other communication scenarios.

Considering the different types of control channels, Shao et al. [Shao et al., 2014] present the MP-MAC protocol, which uses a technique that defines different priorities to transmit a packet, starting with safety packets and then control packets. It uses a multi-priority Markov process to optimize the use of the channel according to the network traffic. Besides, it implements a p-persistent MAC scheme to reduce the probability of collisions during transmission. Table 2.1 summarizes and compares those MAC protocols for VANETs.

2.1.2.3 Network layer

In the network layer, the routing protocol has to implement strategies that provide reliable communication and do not disrupt communication. Vehicular networks support different communication paradigms, as shown in Figure 2.4. These can be categorized as follows:

- *Unicast communication*: the main goal is to communicate data from a source node to a target node via multi-hop wireless communication. The target node may be at a precise known location or an approximate location within a specified range. Despite unicast communication being a helpful model in VANETs, multicast is more suitable

Protocol	**Main Feature**	**Medium Access**	**Advantage**	**Drawbacks**
IEEE 802.11p	A draft amendment to the IEEE 802.11 standard.	CSMA/CA	The design provides reliability and low latency requirements.	It lacks QoS and is not suitable for real-time traffic.
DMAC	Uses directional antennas.	CSMA based.	It improves the performance and reduces collisions.	Assumes that each terminal is aware of the geographic position.
ADHOC MAC	Guarantees a good QoS.	RR-ALOHA	Overcomes the hidden terminal problem and reduces transmission collisions.	The number of slots is fixed.
VC-MAC	Takes advantage of spatial reusability under broadcast scenarios.	Cooperative-ALOHA	Increases the system throughput of the network and reduces the collisions.	Design only to lead with the broadcast scenario.
MP-MAC	Prioritizes safety packets and then controls packets.	p-persistent MAC scheme	Reliable transmission of safety packets and reduced channel collision.	It is not suitable for multi-hop communication.

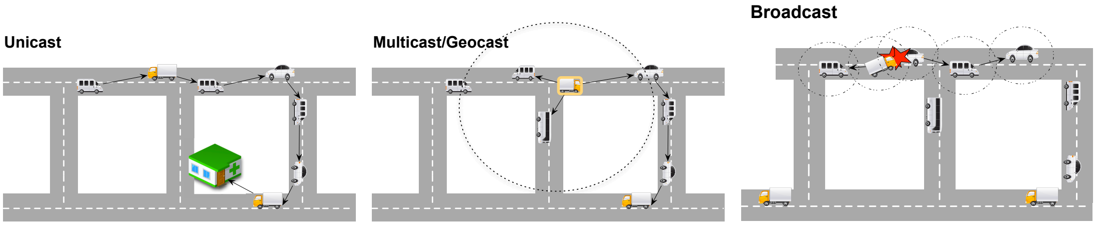
Table 2.1: Comparison among MAC protocols.

for applications that require the dissemination of messages to different nodes in the network.

- *Multicast/Geocast communication*: The main goal is to communicate data from a source node to a group of target nodes. Geocast is a specialized form of multicast addressing in which a message is sent to a group of target nodes in a particular geographic position, usually relative to the message's source.

- *Broadcast communication*: The main feature is to have a source node sending information to all neighbors' nodes at once. The neighbors' nodes that receive the broadcast message forward it through a new broadcast to deliver a message to the target nodes. Broadcast is also used at the discovery phase of some routing protocols in the unicast communication paradigm to find an efficient route from the source vehicle to the target vehicle.

Two basic strategies for data forwarding commonly adopted in multi-hop wireless networks are topology-based and position-based routing [Fonseca and Vazão, 2013; Jerbi et al., 2008; Lee et al., 2010; Nithya Darisini and Kumari, 2013; Slavik and Mahgoub, 2013]. Topology-based protocols use information about communication paths for packet transmission. In this case, every node maintains a routing table, which is the case of routing protocols for MANETs. Topology-based protocols can be divided into proactive (table-driven) and reactive (on-demand). Position-based protocols assume the origin, neighborhood, and destination



(a) Unicast (b) Multicast/Geocast (c) Broadcast

Figure 2.4: Different communication scenarios in VANETs.

locations are known. Position-based protocols can also be divided into delay tolerant, non-delay tolerant, and hybrid. Delay-tolerant geographic routing protocols consider intermittent connectivity, whereas non-delay-tolerant protocols do not and are only helpful in densely populated VANETs. Hybrid approaches take advantage of partial network connectivity.

We could apply routing protocols developed for MANETs, such as AODV [Perkins and Royer, 1999] and DSR [Johnson et al., 2001], to VANETs since a vehicular network is a type of mobile ad hoc network with some distinct characteristics. However, those protocols do not present good performance in VANETs because of fast vehicle movement and relatively high speed of mobile nodes [Li and Wang, 2007]. Conversely, due to the continuous movements of vehicles, position-based routing is more suitable for VANETs. This is a reasonable assumption with the increasing availability of navigation systems in vehicles and improved position accuracy up to a few feet. Furthermore, position-based protocols do not exchange nor maintain link-state information (as opposed to proactive and reactive topology-based protocols). They are more robust and promising in highly dynamic environments like VANETs.

GPSR [Karp and Kung, 2000] is a well-known position-based routing protocol for MANETs based on a greedy forwarding mechanism. That protocol has a route discovery process that leads to significant delays in vehicular networks. Besides, with the rapid movement of vehicles, routing loops can be introduced while in the perimeter mode of GPSR. GPCR [Lochert et al., 2005] and GPSRJ+ [Lee et al., 2007] are position-based protocols based on GPSR, designed to improve the route discovery process in vehicular networks. Since they are position-based protocols, they do not have a global view of the network paths. D-Greedy/D-MinCost [Skordylis and Trigoni, 2008] and VADD [Zhao and Cao, 2008] are position-based protocols designed to consider errors in the route discovery process of GPSR. Those protocols decide whether to forward packets or store them until a better forwarding node is found. They can also reduce packet delays and estimate path delays based on vehicle speed and the number of intersections.

Nevertheless, those protocols must consider more relevant information, like packet traffic congestion. A-STAR [Seet et al., 2004] and CAR [Naumov and Gross, 2007] use traffic awareness for efficient packet delivery. Both protocols deal mainly with network connectivity issues and are not designed to address delay-sensitive applications. PROMPT [Jarupan and Ekici, 2010] is a cross-layer position-based delay-aware communication protocol that improves end-to-end delay using path information gathered by vehicles while propagating beacon messages.

The performance of routing protocols depends on factors such as vehicular mobility models, data traffic, and road layouts. Data dissemination can significantly improve the data delivery ratio if data buffers are located at road intersections Zhao et al. [2007]. There are also some protocols based on link and traffic metrics proposed for VANETs, such as the Multi-hop Routing protocol for Urban VANET (MURU) [Mo et al., 2006] and improved greedy traffic-aware routing protocol (GyTAR) [Jerbi et al., 2007]. In contrast, we still need to investigate the routing performance further when physical, MAC and network characteristics are all considered together [Naumov et al., 2006].

We can enumerate some routing protocols in the literature when considering geo-cast routing. Two approaches to disseminating a message to a group are presented in [Bachir and Benslimane, 2003; Briesemeister et al., 2000]. In this scenario, one message is addressed to a specific set of vehicles according to interest. The key idea of those routing protocols is to consider the position of the vehicles. Thus, according to their position, it is possible to determine whether the message will be helpful. For instance, the presence of obstacles or accidents in a street or highway could require the notification of vehicles. Thus, the first approach [Briesemeister et al., 2000] sends a message to vehicles inside the zone-of-relevance. This zone considers an area where vehicles are to define whether the message is relevant. The other approach, the protocol IVG [Bachir and Benslimane, 2003], determines this area according to the vehicle's driving direction, speed, and position.

Another principle in geocast routing is caching [Maihofer and Eberhardt, 2004] that, aiming to provide excellent performance in delivery, combines the dissemination in a specific area. That approach is based on adding a cache layer to hold packets and only to do the forward when a new node is discovered. Thus, simulation results show that this greedy routing can significantly improve the delivery success ratio.

Regarding reaching all vehicles, broadcast communication is used by a group of protocols that rely on this strategy to establish and organize the routing structure. BROADCOMM [Durresi et al., 2005] is a routing protocol designed for emergency environments. It uses a hierarchy scheme that defines two levels of nodes to broadcast the message. The goal is to improve the QoS features in broadcast communication. Another strategy, the protocol UMB [Korkmaz et al., 2004], is designed to address broadcast storm, hidden node, and reliability problems of multi-hop broadcast in urban areas [Korkmaz et al., 2004]. This protocol achieves efficient use of the channel and a high success rate in delivering a message.

Sun et al. [Sun et al., 2000] propose two strategies to perform a broadcast in a VANET. The first one (V-TRADE) uses a vector distance and GPS information to broadcast the message. The second one (HV-TRADE) uses the position history to guarantee maximal reachability in the broadcast. Table 2.2 summarizes the main characteristics of the protocols mentioned above.

Maia et al. [Maia et al., 2012] propose HyDi, a broadcasting protocol for highway environments. HyDi combines broadcasting suppression strategies and store-carry-forward mechanisms to guarantee message delivery under varying road traffic densities. A limitation of such an approach is its limited applicability under highway scenarios only. Maia et al. [Maia et al., 2013] extend their previous work and propose VoV, a broadcasting solution for urban environments with extreme road traffic conditions. Besides working under different road traffic densities, they offer a rate control mechanism that adapts the protocols to the perceived radio channel condition.

2.1.2.4 Transport and Applications layers

As mentioned above, vehicular networks are characterized by intermittent connectivity and rapid topology changes. In contrast with other ad hoc networks, VANETs present more predictable mobility patterns. In these scenarios, vehicles connecting to an access point at higher speed have a few seconds to download information in an environment with high losses that decrease the performance of both TCP and UDP protocols [Ott and Kutscher, 2004].

In VANETs, many unicast applications require a similar service as provided by TCP, i.e., reliable and in-order data delivery. Unfortunately, TCP presents a poor performance in wireless networks with high mobility and frequent topology changes [Fu et al., 2002]. Vehicular Transport Protocol (VTP) [Schmitz et al., 2006] is a transport protocol for unicast applications in VANETs that probes the network and uses statistical data to improve the performance when a connection is disrupted. Its design is based on the path characteristics relevant to a transport protocol for vehicular networks. Mobile Control Transport Protocol (MCTP) [Bechler et al., 2005] is based on similar principles of the Ad Hoc TCP protocol [Liu and Singh, 2001]. Its main goal is to provide end-to-end QoS between a vehicle and an Internet host via a roadside infrastructure.

These transport protocols for VANETs are designed for applications that require unicast routing. However, many envisioned VANET applications require multicast communication, which requires new approaches not based on traditional transport protocols. Designing a reliable transport protocol for multicast communication is a challenging design problem since multicast protocols usually need to be made more robust.

In the application layer, protocols should minimize the end-to-end communication delay, essential when providing emergency information and delay-sensitive applications. In the former case, depending on the location that generated an emergency event and the position and velocity of the vehicle interested in receiving it, the application protocol may

Routing Protocol	**Comm. Paradigm**	**Forwarding Strategy**	**Architecture**	**Scenario**	**Application**	**Drawbacks**
GPSR	Unicast	Greedy Forwarding	V2V	Real City Traces	CBR Traffic	Greedy forwarding is often restricted to a city scenario because direct communication typically does not exist.
GPCR	Unicast	Packet Forwarding	V2V	Real City Traces	–	It is not indicated in low-density scenarios.
GPRSJ+	Unicast	Greedy Forwarding	V2V	Real City Traces	CBR Traffic	It needs more simulations in more complex and realistic trajectories.
D-Greedy/ D-MinCost	Unicast	Data Muling and Multihop Forwarding	Hybrid	Real City Traces	–	Protocols do not consider local information in the routing decision but only global information.
VADD	Unicast	Packet Forwarding w/ Prediction	V2V	Real City Traces	CBR Traffic	It is not easy to select an outgoing edge freely.
A-STAR	Unicast	Packet Forwarding w/ Traffic Info	V2V	Grid City Traces	CBR Traffic	More appropriate for a city environment.
CAR	Unicast	Packet Forwarding	V2V	Real City Traces	CBR Traffic	The model depends on historical information about the traffic density and average velocity.
PROMPT	Unicast	Packet Forwarding w/ Position Based	V2I	Grid City Traces	Variable Traffic	A simulation w/ realistic model traffic to improve the performance evaluation of the protocol.
MURU	Unicast	Expected Disconnection Heuristic	V2V	Grid City Traces	CBR Traffic	Overhead in the update of the EDD metric is the basis for the routing.
GyTAR	Unicast	Packet Forwarding w/ Street Awareness	V2V	Real City Traces	CBR Traffic	A greedy approach designed for city environments.
Direct Message	Geocast	Packet Forwarding	V2V	Road Traces w/ Accident	–	A simple protocol that uses only a maximal-hop-number threshold limit in a forwarding decision.
IVG	Geocast	Packet Forwarding	V2V	Urban and Rural Road Traces	–	A simple solution that depends on GPS equipment.
Caching Geocast	Geocast	Packet Forwarding w/ caching	V2V	Random Traces	–	In some scenarios, this approach can be affected by the network partition.
BROADCOMM	Broadcast	Packet Forwarding w/ Virtual Cells	V2V	Fixed Traces	Simple Broadcast	Naive performance evaluation.
UMB	Broadcast	Packet Forwarding	Hybrid	Urban Traces	CBR Traffic	The solution has the best performance only in a dense scenario.
V-TRADE/ HV-TRADE	Broadcast	Packet Forwarding w/ Vector Distance	V2V	Urban and Rural Traces	CBR Traffic	The selection of forwarding nodes in every hop causes an overhead.
HyDi	Broadcast	Distance-based	V2V	Highway Traces	–	Only works under highway environments.
VoV	Broadcast	Geographic and Distance-based	V2V	Urban and Random Traces	Video Dissemination	Focuses on video dissemination.

Table 2.2: Comparisons of Routing Protocols in VANETs.

have to comply with real-time deadlines to guarantee that the vehicle's driver will be notified on time about this event. In the latter case, vehicular networks should have a slight end-to-end delay for making infotainment applications involving real-time multimedia available to users.

Application protocols may also be designed to develop marketing tools for business.

For instance, restaurants, hotels, parks, and gas stations can broadcast their information in VANETs, and interested drivers or passengers can send a query to receive more information. Application protocols may also be used in business transactions. Again, such applications require delay-efficient and reliable networks.

Vehicular Information Transfer Protocol (VITP) [Iqbal and Iftode, 2005] is an application-layer communication protocol designed to support establishing a distributed, ad hoc service infrastructure in VANETs. It is based on a location-aware stateless (similar to HTTP) transport protocol for V2I communication.

2.1.3 Applications

Efficiency and safety are two crucial requirements for classifying VANET applications based on their primary purpose. However, efficiency and safety are not entirely separated from each other. On the contrary, those and other aspects should be considered together in the design of VANET applications. For instance, an engine failure or an accident involving two or more vehicles can lead to a traffic jam. A message reporting this event conveys a safety warning for nearby drivers who use it to increase their awareness. The same message may trigger the computation of an alternative route for a vehicle planned to pass through the accident location, but it has yet to be close to that point. In this case, the goal is to increase transport efficiency for individual vehicles. Furthermore, depending on different factors, such as the importance of the accident location, the transport system may compute and suggest alternative routes to a large set of vehicles considering a broader view of the traffic demands to diminish the impact of this event on regions not close to the accident. In this case, the goal is to increase overall transport efficiency. Note that in both cases, an early event notification can help a driver or a passenger to decide to take a different route, use various means of transport or even stay at the current location in case of a severe traffic problem. In this case, an additional goal is to provide a person with helpful information in planning an activity related to the transport system.

VANET applications will monitor different types of data such as vehicle conditions, surrounding roads, approaching vehicles, the surface of the road, and weather conditions to make the infrastructure more secure and efficient. Once this data is available, vehicles will communicate via wireless communication networks among the other vehicles exchanging the relevant information for different purposes. According to Table 2.3, in the following, we briefly discuss some of the existing and future applications for VANETs.

Safety Applications: The ultimate goal of safety applications in VANETs is to avoid and decrease the number of road accidents. This is an application category sensitive to the delay. Thus, applications use vehicle-to-vehicle communication to reduce the delay in this category. Another requirement is reliability; all vehicles close to the hazard must be alert. If a collision occurs, there are two issues to deal with: the approaching vehicles and the accident location. Simple applications like sending emergency notifications to a call center that already transfer the notification to emergency responders, such as the GM's OnStar system [General Motors', 2010]. Whenever an accident happens, an event (e.g., the release of an airbag) triggers a notification system to send emergency messages to nearby emergency responders. These notifications may carry the position provided by a GPS-enabled device. For future applications, depending on the distance to the accident that occurred further along the road, this application must warn the driver or even automatically brake the vehicle (e.g., emergency braking) when the distance decreases under a specific limit. Emergency video streaming to help emergency responders (paramedics, firefighters, and other rescue personnel) is highly desirable. Before arriving on the scene, they could know the geographic location of the vehicle and traffic conditions at the site to respond more strategically to the incident. This video information can be obtained from vehicles equipped with video cameras capable of storing and forwarding images. The application could also monitor the post-collision scenario, taking appropriate actions and executing them promptly. Once an accident has occurred, the application should manage vehicle flows and identify alternative routes to either individual or a large set of vehicles, according to the accident location, time of the day, and other factors. Of course, a safety application should be designed to act proactively, providing drivers with early warnings and preventing an accident from happening in the first place.

Efficiency applications: This is a category where the applications know the vehicle location, aiming to improve their mobility within the public roads. In this category, most applications require high availability because the drivers need the information provided to make decisions during the trip, making the voyage more secure. The communication pattern generally occurs among the vehicles and from vehicles to roadside units. We can classify these applications in two ways: applications to control crossroads and intersections and applications to reduce and avoid traffic jams.

- Crossroads and intersections: Traffic control and management is an important research area that can benefit VANETs. For instance, vehicles passing near and through intersections should drive carefully since two or more traffic flows converge, and the possibility of collision increases. In this scenario, virtual traffic lights could control and manage the traffic flow at intersections. Another safety application is to warn the driver of an impending collision, who can take proper actions to prevent it. In both applications, i.e., virtual traffic lights and safety, stringent requirements must be addressed, mainly related to real-time constraints and distributed processing.

- Road congestion management: A road congestion application can provide drivers with the best routes to their destinations and determine the best time schedules for traffic lights along the overall routes. The goal is to decrease congestion on the involved roads and maintain smooth traffic flow. This could increase the road capacity and prevent traffic jams.

Comfort applications: In this category, drivers can receive information from vehicular services that may help them drive during the trip making it more comfortable and enjoyable. Usually, the typical application requirements are reliability and availability providing the information at the right moment that the driver needs. Such application type comprises weather information, gas station or restaurant location, city leisure information, tourist information, information on the available parking lot at a parking place, international service handover, road charging, route navigation (e.g., estimated journey time, recommended information based on the user's context, automatic road map update, civilian surveillance) and advertisements or announcements of location-based sales information. In many cases, communication will happen between vehicles and roadside units, with no demand for large bandwidth.

Interactive entertainment: Aiming to distribute and deliver entertainment-related information to drivers and passengers, this application category has as its main features connectivity and availability. Thus, communication patterns can happen directly among vehicles or between vehicles and roadsides. Ideally, the information should be tailored to the users' context. The challenge here is to keep this context information up-to-date, considering the dynamics and mobility of vehicles and people in a VANET. After all, the synchronization among vehicles and central servers becomes a significant challenge in this context. Examples of applications in this category are Internet access, distributed games, microblogs, chats, music downloads, web browsing, file sharing, home control, etc. In future generation applications, passengers can interact with passengers in nearby vehicles or with people anywhere in the world through instant messaging services, games, and even videoconference.

Urban sensing: A vehicular network can be seen as a paradigm for urban monitoring and sharing common interest data. This is particularly true in urban areas, where we can expect a high concentration of vehicles equipped with onboard sensors. Vehicular networks can effectively monitor urban areas' environmental conditions and social activities, playing an essential role in urban sensing [Cuff et al., 2008; Uichin Lee et al., 2009]. Urban sensing applications can be further potentialized when smartphone capabilities have been taken on board and can be used complementarily with VANET sensors [Lee and Gerla, 2010; Lo et al., 2013]. In this context, the design of a Vehicular Sensor Network (VSN) introduces new and challenging issues, which are considerably different from traditional wireless sensor networks, thus requiring innovative solutions. This research area is promising since energy constraints and other restrictions do not affect vehicles. Vehicles can be equipped with powerful processing units, different wireless communication devices, navigation systems, and many sensing devices such as chemical detectors, vibration/acoustic sensors, and still/video cameras. The combination of vehicular and sensor networks presents a tremendous opportunity for different large-scale applications in VANETs, ranging from traffic routing and relief to environmental monitoring, distributed surveillance, and mobile social networks.

Table 2.3 summarizes the main characteristics of the discussed categories, where applications are classified according to their features, communication requirements, existing protocol solutions, and pull-based vs. push-based mechanisms.

Application Class	**Characteristic to consider**	**Architecture**	**Location Awareness**	**Time Awareness**	**Communication Technology**	**Desirable properties of protocols**	**Challenges**	**Push/pull based**	**Application Examples**
Safety	Delay	V2V–V2I	Yes	Yes	DSRC/RFID/ Bluetooth/Wi-Fi	Reliability	Reduce the latency	Push based	Collision alert; Intersection collision; pedestrian crossing warning; bike/motorbike lane changing.
Efficiency	Availability	V2V–V2I	Yes	Yes	DSRC	Real-time and reliability	Availability Of services	Pull based	Traffic flow; road condition; dangers on the road.
Comfort	Reliability	V2I	Yes	No	WiMAX/Wi-Fi/ 3G/4G/LTE	Real time	Support on-demand applications	Pull based	Free parking space; Music Downloads; Play videos.
Interactive Entertainment	Connectivity and availability	V2V–V2I	No	Yes	3G/LTE/Wi-Fi/ WiMAX	Unicast Communication	Keep synchronization	Pull based	Games; synchronous activities and other Internet activities.
Urban Sensing	Mobility	V2V–V2I	Yes	Yes	DSRC/3G/LTE/ Wi-Fi/WiMAX	Data collection	Security in data communication	Pull/push based	Photographs, road conditions, etc.

Table 2.3: Categorization of VANETs Applications.

2.2 Chapter remarks

Wireless vehicular networking is a key enabling technology for future intelligent transportation systems, smart vehicles, and smart infrastructure. The advent of vehicular networks comprised of vehicles equipped with the ability to establish wireless communications and self-organize into a collaborative mesh opens countless applications that can make road travel safer (by avoiding collisions), more efficient (by decreasing travel time, avoiding traffic congestion, and increasing road capacity), and more pleasant to the users. VANETs will likely become the most important realization of mobile ad hoc networks.

The distinct characteristics of VANETs lead to specific networking problems, demanding the design of fully distributed protocols. VANETs introduce additional challenges for protocol designers besides those already in mobile ad hoc networks. In particular, the mobility of vehicles results in a dynamic scenario with a substantial rate of link changes and, consequently, a very short lifetime for multi-hop paths. In this case, protocols that need to know the system's state (even if only local) could be more efficient due to frequent network changes. In addition, VANET applications may require (or benefit from) a different protocol stack.

Many exciting research challenges in different areas that need to be incorporated into actual deployment have yet to be solved since innovation heavily depends on technology acceptance. During the last decade, significant advances in VANET research and the associated technology have sparked much interest in different research communities, such as transportation, wireless communication, and networking. Several automotive companies, research institutions, and government organizations are evaluating, proposing, creating, and engineering future VANET systems. These will come from opportunities and synergies of connected vehicles and infrastructures. A common and fundamental aspect of vehicular networks is the different types of algorithms employed in VANETs.

This chapter discussed the main characteristics of vehicular networks, architecture details, constraints of layers, protocols, applications, and future perspectives. The insight discussed here will help protocols' designers and applications engineers improve the services provided in this network and assist drivers in making secure trips.

CHAPTER

3

Interactions on Vehicular Networks

> "Everyday interactions we have with other people are definitely contagious, in terms of happiness."
>
> Nicholas A. Christakis

3.1 Introduction

Vehicular Networks (VANETs) are an emerging type of network that has attracted the research community's interest due to their potential to enable safer and more efficient roads. VANETs are vehicles equipped with processing, sensing, and communication capabilities. During their trajectories, vehicles can exchange information with other vehicles and entities from other networks, such as the Internet. Unlike other networks, nodes in VANETs are vehicles such as cars, buses, taxis, and trucks with a wireless communication interface. They communicate among themselves and with the roadside units (RSUs) located along the roads Cunha et al. [2016].

To create a vehicular network and promote communication among vehicles, it is important to understand which entities compose a vehicular network and how these entities interact with each other. In a vehicular network, we identify vehicles, mobile devices, and smart infrastructure (RSUs, smart signs, and sensors) as examples of entities. In this scenario, an interaction can be defined as *"an occasion when two or more people or things communicate with or react to each other"* [Press, 2015], i.e., in the context of vehicular networks, interactions occur whenever there is a communication between two or more entities. For instance, when

Figure 3.1: Main entities present in Vehicular Networks.

moving along the roads, vehicles may interact with the smart infrastructure, such as speed limits and direction controllers, which directly impacts road traffic. Besides, interactions among vehicles, mobile devices, and the smart infrastructure provide drivers with information such as obstacles, crashes, and traffic jams ahead, allowing them to change routes.

Many factors may impact interactions. First, we point out mobility as the most significant influence factor. Usually, vehicles that cross many streets perform long trajectories and visit many places. Thus, they tend to interact with a large number of other vehicles and other entities during their routes. Besides, the trajectories are also closely related to the drivers' behaviors since their routines influence the places they visit and the periods of the day those visits occur.

Moreover, another factor that impacts the interactions is the weather. Weather variations can contribute to increasing or decreasing the traffic density, e.g., when it is raining, the drivers need to be more careful with the road conditions. Therefore, they decrease their speeds or even avoid certain trips [Sukuvaara et al., 2015].

Aiming to understand better the operation of vehicular networks and how communication happens on them, this work aims to study the interactions and how they can exist and impact VANETs. Considering this knowledge, designing new services and protocols that are more robust and efficient will be possible. Thus, in this chapter, we will describe the entities involved in interactions that play some role in VANETs, discussing their existing interactions. Also, we present an overview of the factors that can impact interactions and applications created due to these interactions.

This chapter proceeds as follows. In Section 3.2, we present the entities that comprise a vehicular network. Section 3.3 discusses the types of interactions among the defined entities. Section 3.4 presents the factors that may impact the interactions. Section 3.5 presents the entities and the communication patterns employed by each application type. Section 3.6 discusses some perspectives on user interactions to improve communication in VANETs. Finally, in Section 3.7, we draw important remarks and future directions.

3.2 Entities

Differently from traditional ad hoc networks, in VANETs, vehicles travel on the roads while exchanging data among themselves and with RSUs. However, vehicles may also interact with other entities during their trajectories, aiming to promote services to drivers and passengers, making their trips safer and more enjoyable. Therefore, we identify *vehicles, mobile devices, and smart Infrastructure* as the main entities that compose a vehicular network. Figure 3.1 presents the main entities of a VANET with examples. In the following, we define each entity, describing behaviors and features.

Vehicles: can receive and send data. They drive on the streets and highways, exchanging data among themselves. Vehicular networks have different types of vehicles, such as cars, motorcycles, bikes, buses, tramways, and trucks. Each vehicle type has its features and behaviors, which influence interactions differently.

First, the vehicles' purpose determines destinations, routes, speed, number of daily trips, period on the road, and the driver's behavior. We identify particular commercial, emergency, and transport public vehicles as the primary vehicles' purposes. In particular vehicles, the mobility pattern depends on the driver's wishes, which vary according to the passenger's routine and the weekdays. Commercial vehicles have routes planned according to a set of places to visit. Also, these routes are defined aiming to reach the final destination and reduce the trip duration.

Transport public vehicles have the goal of transporting people to their destinations. Transport public vehicles can be divided into taxis, buses, and tramways. Taxis produce random mobility, reflecting the final destinations of different people. Moreover, we can find them all day and night, including day breaks. Buses and tramways carry people in short distances (inside the city) or long distances (between cities). In both scenarios, buses have a schedule to start the trips and a pre-established route.

Mobile Devices: With the growth of mobile computing, people use different mobile devices, enabling them to interact with many other services and networks [Burke et al., 2006]. Mobile devices include smartphone, pad, laptop, watch, camera, and wearable devices. In the context of a vehicular network, these devices can be used for sensing a traffic event, informing drivers about hazards, promoting entertainment services, or assisting drivers aiming to reach the final destination.

These devices can vary according to configuration features, such as operating system, storage and processing capacity, and communication technology (e.g., Bluetooth, Wi-Fi, 3G, 4G). Moreover, many different applications users employ to send data to drivers, passengers, and online services on the Internet.

Smart Infrastructure : is the set of devices that enable communication among vehicles and other network devices. It comprises RSUs, sensors, traffic lights, and panel signs that

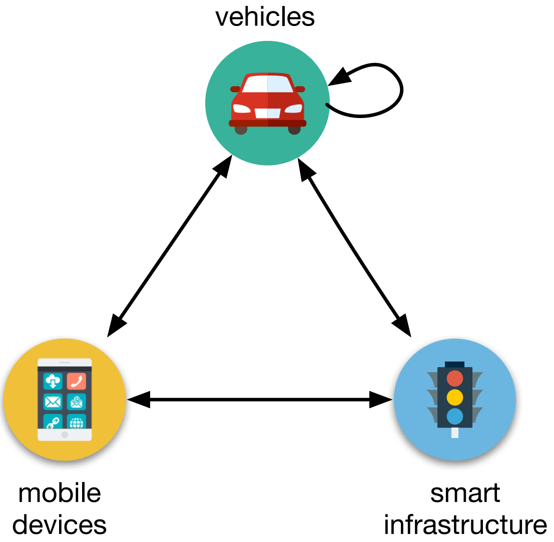


Figure 3.2: Graphical representation of interactions in vehicular networks

cooperate to create an intelligent traffic system. Sensors can measure the vehicles' speed, monitor the density of vehicles in an area to predict the traffic and dynamically adjust traffic lights, enable automatic payment in tolls, monitor road conditions, and enable the navigation of autonomous vehicles.

Like LAN access points, RSUs are installed near or along the roads or highways. These units aim to allow communication between vehicles and fixed communication infrastructures, such as the Internet. Therefore, through RSUs, vehicles can interact with different Internet applications, retrieve data from various sensors, and communicate with other vehicles outside their communication range.

3.3 Interactions

In the previous section, we discussed the entity types found in VANETs. Herein, we explain the possible interactions that may happen among those entities. Hereafter, we present the interactions among the entities according to the relationships outlined in Figure 3.2.

3.3.1 Vehicles to Vehicles (V2V):

One of the main goals of VANETs is to enable communication among vehicles to promote safer driving by reducing the number of incidents. Such communication occurs due to the interaction among vehicles, i.e., when two or more vehicles are inside the communication range of one another, allowing them to directly exchange data, as illustrated in Figure 3.3-(a).

Vehicular applications rely on these interactions to provide different services to the network. For instance, warning services use these interactions to quickly deliver alert messages to vehicles inside a region of interest to notify drivers about road hazards. However, due to the characteristics inherent to VANETs, the duration and the frequency of these interactions are highly dependent on many aspects. For instance, the time of the day directly impacts the traffic in a city. During rush hours, traffic jams are more likely to happen. Therefore, a vehicle stuck in traffic is temporarily restricted to interactions with only vehicles in its surrounding.

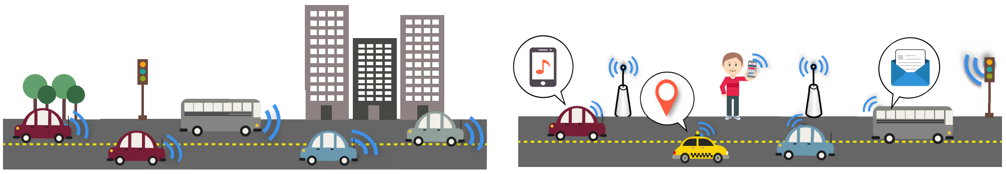
3.3.2 Vehicles to Mobile Devices (V2M)

According to Figure 3.3-(b), interactions between vehicles and mobile devices occur under different situations. Passengers can connect their devices to vehicles to make phone calls, listen to music, send instant messages, or browse the Web using a voice command. Likewise, drivers can also use their devices to retrieve information about routes, traffic conditions, nearby attractions, etc. For instance, drivers can use special glasses to improve their vision, exhibiting more information about roads, obstacles, or hazards.

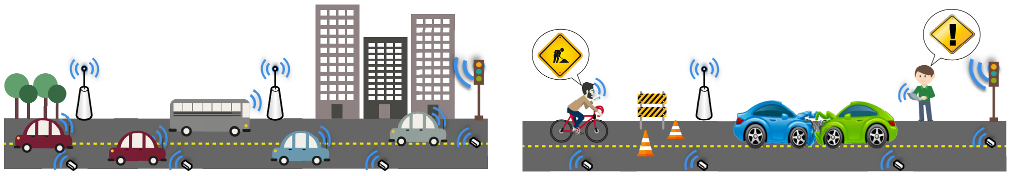
Moreover, during their trips, passengers can interact with the Internet through multimedia devices to access Web pages or download Web content on their devices. In another context, some applications use pedestrians' mobile devices to sense traffic conditions or road hazards to notify nearby drivers.

3.3.3 Vehicles to Smart Infrastructure (V2I)

When considering interactions between vehicles and the smart infrastructure (Figure 3.3-(c)), we can highlight those between vehicles and RSUs, which enable both the communication among vehicles that are geographically apart from one another and direct access



(a) vehicles to vehicles (b) vehicles to mobile devices



(c) vehicles to smart infrastructure (d) mobile devices to smart infrastructure

Figure 3.3: Interaction patterns among the entities in vehicular networks

to different networks, such as the Internet. For instance, when the density of vehicles is low, and multi-hop communication through vehicles is not possible, a vehicle can alternatively send data to a nearby RSU, which will be responsible for delivering it to distant intended recipients using wired or wireless communication. Moreover, whenever fixed infrastructure (e.g., 3G, 4G) is temporarily unavailable, onboard services of vehicles can alternatively use RSUs to connect to the Internet.

In fog computing, an RSU can be used as a server to locally process and store data about its surroundings [Stojmenovic and Wen, 2014]. Therefore, responses to vehicle requests can be quickly provided. For instance, users can request the best route to a navigation application, which uses the RSU to perform the local computation and quickly answer the request.

Another type of smart infrastructure is sensors available on both vehicles and roads. For instance, sensors may monitor free slots in parking lots. This way, a vehicle can interact with those sensors to identify the best free slot according to some criterion. Moreover, interactions with sensors may be used by authorities to verify vehicles' conditions, toll collection, and tracking. Vehicles may also interact with sensors to retrieve data about road and weather conditions.

On-board vehicle sensors can provide the driver with different data types, such as vehicle temperature, fuel level, speed, water level, etc. Through interactions with onboard sensors and RSUs, drivers can schedule the best time to refuel the vehicles and search for the nearest gas station with the lowest price. In the context of intelligent cities, road sensors are used to assist self-driving cars. An autonomous vehicle can communicate with those sensors and use GPS to calibrate the car's direction and keep the vehicle's speed according to the road's limits.

3.3.4 Mobile Devices to Smart Infrastructure (M2I)

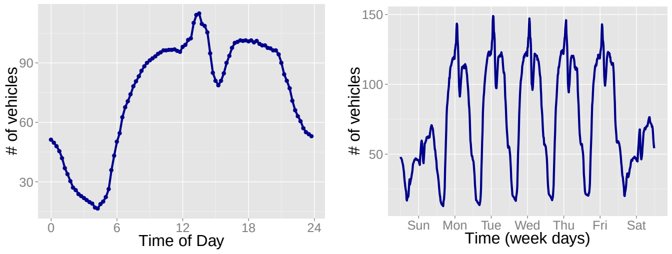
Many services rely on the interaction between mobile devices and the smart infrastructure, as shown in Figure 3.3-(d). Typically, drivers obtain traffic information through applications installed on mobile devices, which interact with a group of sensors, such as road sensors, street cameras, and the vehicle's GPS. For instance, using data collected from these sensors, an RSU can provide re-routing services that evaluate the traffic level on each lane and recommend faster routes. Moreover, mobile devices may be used to complement the deployed smart infrastructure through the use of participatory sensors network application [Burke et al., 2006]. The idea is for mobile users to use their smartphones as mobile sensors, monitoring the environment, weather, urban mobility, and traffic conditions.

3.4 Factors that impact on Interactions

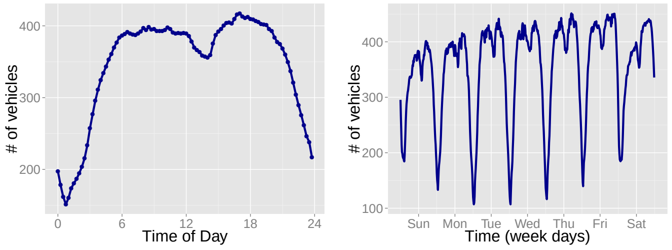
When we look at the interactions among entities, some questions help us to understand them better, such as: *What is the time of day that has the highest number of interactions?*, *Are there some places in the city that favor the occurrence of interactions?* or *What is the influence the environment plays on the interactions?*. Considering these questions and other environmental features, we describe the factors influencing the interactions in the following. These factors can be used to improve the design of protocols and services for vehicular networks.

Driver's Behaviors: A person who chooses the destination can be influenced by many factors, such as the time of day, weekday, special events, his/her desires, etc. All of these factors are directly related to people's routines. People take vehicles to school, work, the hospital, and the gym on weekdays. At weekends, people use their time to pleasure themselves by going to the cinema, theater, camping, malls, etc. Besides, in special events such as musical concerts, games, and festivals, the concentration of people increases at specific points in the city, and the roads around these places can present many traffic jams. In all these moments, people travel across many roads, thus changing the vehicular density, directly affecting the number of interactions the vehicles perform.

Time: Considering the influence of time on the interactions, we can highlight the difference in the vehicle's density over the day and the week. During the day, it is possible to identify peak hours, i.e., when there is an excellent density of vehicles in transit. Usually, this period occurs at the beginning and end of the day, hours when people start their routines,



(a) Rome daily (b) Rome weekly



(c) San Francisco daily (d) San Francisco weekly

Figure 3.4: Traffic evolution over the day and week, in two cities: Rome and San Francisco

going to the same places, such as offices and schools, and then returning home. Weekdays and daybreaks also produce traffic variations. These are the periods when the traffic is sparser and quieter, and people tend to choose other destinations, such as malls and leisure areas.

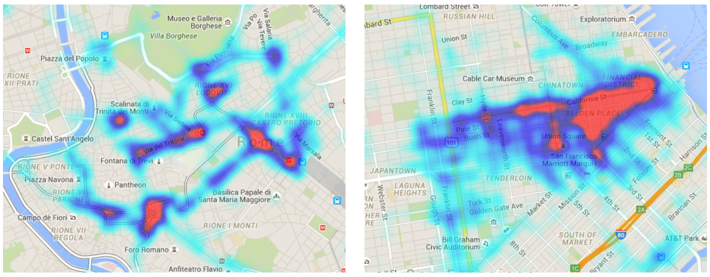
To illustrate this influence, Figure 3.4 presents the traffic evolution for two dataset traces, describing the taxi mobility in Rome and San Francisco daily and week. Indeed, in Rome, we can observe a significant difference between weekdays and weekends, i.e., on weekdays, we observe rush hours, when interactions are more frequent. Due to local features, the traffic is lower on weekends than on weekdays. We can also note a variation over the daybreak, when the demand for trips reduce, and interactions are less frequent during this period.

We also note a slight difference between weekdays and weekends in San Francisco. We observe higher traffic over the day, a period with more interactions. Moreover, we observe a lower traffic period during daybreak, when the number of interactions also reduces. Thus, analyzing the daily traffic makes it possible to identify the periods that favor the interactions among the entities.

Weather: Weather events may affect roads by impairing visibility, obstructing lanes, and damaging infrastructure, which implies delayed trips, reduced roadway capacity, and increased risk of accidents. Also, these events lead to changes in the driver's behavior, directly affecting traffic and possible interactions. For instance, drivers decrease vehicles' speed and increase their headways, aiming to avoid car crashes. However, bad weather conditions increase interactions among vehicles and the smart infrastructure since drivers rely on information about road and weather conditions to improve their driving capability. Besides, in this scenario, the number of reports mobile users provide increases because road crashes and hazards also increase.

Points of Interest: Considering the features of a vehicular scenario, each trip has a defined departure and arrival point. Therefore, the choice of these points depends on many factors, such as people's wishes, routines, and the period of the day. However, the purpose of the place can also influence the choice. For instance, places that group stores, malls, and restaurants tend to attract people who want to shop and eat. Park and tourist places attract people who are looking for leisure. Moreover, the downtown region of a city concentrates a significant number of offices and enterprises, which increases the number of vehicles during the weekday. In these areas, the density of vehicles tends to be higher, increasing the likelihood of having more interactions among vehicles.

Figure 3.5 presents a Rome and San Francisco taxi dataset heatmap. Based on these maps, we can observe places with more taxi interactions during rush hours.



(a) Rome (b) San Francisco

Figure 3.5: Heatmap representing the interactions in the rush hours over space in Rome and San Francisco cities

Festival and Special Events: Special events generate large traffic volumes due to the sudden increase of people in a single place. Usually, these events demand traffic planning and heavy use of public transportation to transport people attending the event. The goals are to reduce traffic jams, parking problems, and, in some cases, the communication problem. Due to the high concentration of people and the shared wireless medium, mobile communication can be affected, hindering the interaction among vehicles and other entities.

Road conditions: Road conditions can vary due to many events, such as traffic jams, incidents, protests, breakdowns and debris in travel lanes, roadwork, falling rocks, and other events that may disrupt the normal traffic flow, thus increasing the trip time. When facing these situations, drivers need to change their routes, looking for new trajectories and shortcuts that reduce the impact of these events. Using interactions with assistant services, they can change their routes and send reports to other drivers warning them about road obstructions or bad conditions.

Context information: In vehicular networks, the context information is applied to portray the driving situation, such as position, direction, and acceleration of the vehicle, the period of the day, the traffic and weather forecast, and others [Vahdat-Nejad et al., 2016]. However, due to VANET features, this information frequently suffers changes, requiring applications to be aware of these changes and increasing interactions among entities. For instance, applications that avoid collisions must know the vehicles' positions. The application must warn the drivers as soon as the collision possibility is detected.

3.5 Applications

In vehicular networks, most applications are designed to assist drivers during their trips, aiming to reduce accidents and manage traffic. However, some applications aim to make trips more enjoyable. This section discusses the main applications, providing an overview of each category.

Safety Applications: The main focus of this application type is to make driving safer by avoiding crashes and forecasting dangerous situations. In many cases, these applications assist drivers by providing information to help them react to a bad situation. To monitor the traffic and warn the drivers, interactions among vehicles, sensors, RSU, and mobile devices are every day. For instance, to monitor the speed and the distance among vehicles; to obtain the roads' configuration and the vehicles' positions [Ferreira et al., 2015]; to compute the number of vehicles in transit; and to deliver the message to drivers to warn them about hazards ahead.

Efficiency Applications: In this category, we can find all applications that work to simplify and improve the driving process. Through interactions among entities, these applications monitor roads, traffic conditions, and dangers on the road. Moreover, it is possible to suggest routes to drivers, avoiding obstacles and traffic jams. With the help of RSUs, it is possible to suggest new routes to drivers according to real traffic conditions. Furthermore, interactions can also enable the download of local maps, which will assist the drivers on their trips Dashtinezhad et al. [2004].

Comfort Applications: These applications enable drivers to receive information from Internet services and other vehicles to make the trip more comfortable and pleasant. These comprise applications such as weather information; free parking slots [Zhao et al., 2012]; route navigation; tool and gas automatic payment; advertisements or announcements of location-based information [Lee et al., 2006]; reviews and suggestions of hotels and restaurants; and file exchange [Yousefi et al., 2010]. These solutions are provided by the interactions among the RSUs, physical and social sensors, mobile devices, and vehicles. Also, they should be aware of the intermittent connections common to VANET scenarios.

Interactive Entertainment: In this category, we have all the applications that work to provide entertainment to drivers and passengers during their trips. Among these applications, we can mention music downloads, video streams, instant messages, real-time applications, and other Web content [Wei et al., 2014]. For instance, a user can request content during his/her trip, and due to interactions among vehicles and RSUs, the appropriate content will be delivered to the user. Therefore, to keep the application working during the trip, the RSUs installed along the vehicle's trajectory should interact among them, aiming to keep constant connectivity.

Urban Sensing: A VANET can monitor and share data about many traffic features. Due to the city coverage by the vehicles in transit, these networks allow more accurate sensing of events and more collected data. A modern vehicle is expected to have many sensors, increasing the number of events it can monitor. In this context, we can highlight some applications, such as monitoring hazards on roads and highways, detecting the presence of animals, obstacles ahead, weather conditions on the road, traffic forecast, and others [Barbagli et al., 2011]. For instance, in an application to monitor these events and send alerts, there are interactions among mobile devices, vehicles, and sensors to detect the events, besides interactions among vehicles and RSUs to disseminate the alerts. Data sensing in VANETs opens up new trends and exciting issues in the design of vehicular sensor networks Lee and Gerla [2010].

3.6 Using Interactions

The study of interactions in vehicular networks can open new perspectives. When considering the communication point of view, this study brings out new features to consider in designing communication protocols. For instance, by understanding the frequency of interactions, it is possible to identify the best vehicles to perform a message broadcast, aiming to increase the message coverage and reduce the message delivery delay and redundancy. For instance, in [Cunha et al., 2014b], we present a new solution for data dissemination by exploring interaction features. When considering the frequency of interactions, it can be classified as random or frequent. This property helps identify vehicular interactions that are or are not predicted. Thus, it is possible to identify the vehicles with the same behaviors and routines and then explore these vehicles to improve the routing process, for instance.

When considering the network design, knowledge about the interactions can help identify the places more likely to induce new interactions, ensuring vehicle connectivity. Thus, new RSU placement strategies can be applied. Also, the frequency of interactions among sensors and vehicles can be used to identify the places with a higher probability of accidents. Thus, more sensors can be installed on the roads to assist drivers and reduce the number of crashes.

3.7 Chapter remarks

A vehicular network is a key enabling technology for future intelligent transportation systems, smart vehicles, and smart infrastructure. The fact that this network is composed of vehicles with sensing and communication capacities creates countless applications that make the trip safer, more enjoyable, and more efficient, reducing travel distance and duration.

Bearing in mind all the aspects and features of VANETs, in this work, we addressed the entities that interact among themselves to provide communication among vehicles and other types of networks. We discussed the interactions among entities and the factors that affect those interactions. We also discussed possible applications that might arise in these interactions.

We hope the insights discussed here will help researchers in new studies of vehicular networks once they consider the main interactions among entities that encompass these networks. Moreover, better applications can be developed when taking into account those interactions. Besides, other studies can be conducted to characterize the interaction level between each entity (e.g., how and where the interactions happen, the frequency and duration of the interactions) and to explore the described factors that have some influence on the interactions.

CHAPTER

4

Characterizing Social Interactions

> "All our knowledge has its origins
> in our perceptions"
>
> Leonardo da Vinci

4.1 Introduction

In Vehicular Networks, communication is highly influenced by the vehicles' mobility patterns. The vehicles move and stop according to interactions with the drivers and the speed limits and directions imposed by the regulatory signs. However, daily interactions, driver routines, and vehicles can influence this mobility. Observing the weekday traffic, we cannot rush hours with the traffic slow in some streets and traffic jams. On the contrary, the traffic is quieter in the early mornings and weekends, with low vehicle density. This traffic variation on different days and hours reinforces the character of the dynamic topology of VANETs, making communication a challenging task in some scenarios.

Also, mobility is influenced by the behavior of the driver and its routine. During the weekends, destinations such as camping, malls, and churches are chosen for leisure and entertainment and are frequently visited. However, on weekdays people repeat their paths simultaneously and to the same destination, such as school, work, offices, university, restaurant, coffee shops, etc. During their trajectories, vehicles encounter other vehicles, pass in the same streets, and are subject to the same traffic conditions. These presented features suggest the study of vehicular mobility from a social perspective to understand the interactions they present during their trajectories. Also, to improve the connectivity and services in VANETs, it would be interesting to find vehicles that present the same destinations and have similar behavior.

To characterize the daily traffic evolution, the routines, and the driver's behavior, in literature, many works perform the mobility analysis of vehicular networks [Fiore and Härri, 2008; Pallis et al., 2009; Loulloudes et al., 2010; Liu et al., 2012]. However, these are works based on analytical mobility models or realistic traces, and the analysis considers short periods. In this chapter, we investigate the following question: *How do vehicles interact in a vehicular network?* Thus, we present a statistical and social network analysis of synthetic and real traces that describe the vehicles in the great cities, extracting properties and behaviors from the mobility to verify how the vehicular interactions are performed over the day.

The remainder of this work is organized as follows. Section 4.2 presents a brief survey of the related work. In Section 4.3, we present the main features of the analyzed dataset. Section 4.4 describes the methodology used to characterize interactions. In Section 4.5, we present the quantitative results. Finally, in Section 4.6, we present the final remarks and future perspectives.

4.2 Related work

"Computer networks are inherently social networks, linking people, organizations, and knowledge"[Wellman, 2001]. In this perspective, the concepts of social networks have been explored in different kinds of computer networks, mainly to understand the evolution of the network topology and to analyze the nodes' physical encounters to improve the performance of the network protocols.

When we look at the literature, it is possible to find works that focus on the analysis of physical encounters of the nodes on the network, aiming to understand the evolution of the network topology and the connectivity among the nodes. Due to their peculiarities in vehicular networks, performing traffic mobility analysis to improve protocols and service performance is interesting. In this way, in [Fiore and Härri, 2008], the authors present a depth analysis of the topological properties of vehicular networks, where it was explored the social metrics in different mobility models. They used social metrics to investigate the temporal evolution of the network topology. Results show that it is possible to take advantage of vehicular mobility to improve the performance of the network protocols. However, this work is based only on analytical mobility models.

In the same context, in[Pallis et al., 2009] and [Loulloudes et al., 2010], the authors discuss how social metrics can be employed to improve the performance of the routing protocols in urban vehicular networks. They perform the analysis in realistic and real traces, and the results show the importance of considering topology aspects to design the new routing protocols. Nevertheless, the analysis is based on only 2 hours of the traces, not considering the whole dataset. Also, the work presented in [Liu et al., 2012] discusses several universal laws of social networks, presenting an analysis of two dataset traces. However, the authors only consider fewer vehicles and three social metrics, i.e., node degree, distance, and cluster coefficient.

In [Uppoor and Fiore, 2012], a macro and microscopic evaluation of the Cologne trace is presented. The macroscopic analysis involves the evolution of vehicular density and the dynamics of large-scale flows of vehicles through the metropolitan region. The microscopic analysis considers the distribution of vehicles in the area and the encounters among them. They present the evolution of the traffic over the area and time, highlighting the importance of designing protocols and services for vehicular networks considering the dynamism of road traffic. In [de Melo et al., 2015], the authors present a strategy to analyze users' interactions in dynamic networks. They define a way to classify user interactions among random and social relationships.

Similarly, the authors evaluated mobility traces describing different users type. However, they use a long slot time, which groups all encounters during one day. In our work, we will consider the trace duration, figuring out how the interactions happen among the taxis and the environment.

4.3 Vehicular mobility traces

In this Section, we describe the vehicular traces found in the literature available to perform the analyzes, the calibration method used to fill the gaps in the traces, and the mobility model that represents the vehicular traffic during working days over the city.

4.3.1 Original Traces

Traces are a particular dataset type that contains information about the trajectory of vehicles to track the vehicles' mobility during a trajectory. Such traces are attractive since they exhibit the real behavior of vehicles in a certain scenario, and in the literature, there are real and realistic traces. The real traces contain information collected from vehicles using some localization system device (e.g., GPS). The realistic traces are created by the junction of maps of a particular locality, traffic information of this locality, and a mobility simulator.

We describe the main features of the two traces used in our evaluation and present an initial traffic analysis.

San Francisco: This real trace contains mobility traces of taxi cabs in San Francisco, USA. Each taxi has a GPS receiver, and the trace contains GPS coordinates, in each minute, of 500 taxis, collected over 30 days in the San Francisco area, from May 17 to June 10 of 2008 [Piorkowski et al., 2009].

Rome: This real trace contains mobility traces of taxi cabs in Rome, Italy. Each taxi has a GPS receiver, and the trace contains GPS coordinates of approximately 320 taxis that work in the center of Rome, collected over 30 days in the Rome area, from February 01 to March 02 of 2014 [Bracciale et al., 2014]. Each taxi driver has a tablet that periodically (7 seconds) retrieves the GPS position and sends it to a central server.

Zurich: A multi-agent traffic simulator developed by ETH Zurich created a realistic trace for Zurich, Switzerland [Naumov et al., 2006]. This trace contains public and private traffic with high levels of realism, reproducing the behavior of a large city during 24 hours. With 25,000,000 records (direction/speed) of 260,000 vehicles, the trace covers an area of 250 km × 260 km.

Shanghai: The SUVnet-trace is a real trace with the GPS information from more than 4,000 taxis in the Shanghai city [University, 2007]. This taxi group has been observed during 28 days, from January 31 to February 27 of 2007.

Cologne: The TAPASCologne Project is a realistic trace that reproduces with the highest realism the car traffic in Cologne city, in Germany [C. Varschen, 2006]. The process to make this trace includes necessary literature tools like OpenStreetMap, SUMO simulator mobility, and information on traffic demand in the city. It brings the information of 700,000 records of individual car trips during 24 hours in an area of 400 km^2.

Luxembourg: This is a realistic trace that presents commuting traffic over the area of Luxembourg [Pigné et al., 2011]. It has been generated by the VehiLux model and augmented with Gawron's dynamic route assignment algorithm. The trace covers an area of 51km × 44km during 11 hours and has 110,188 records.

4.3.2 Calibrated Traces

Vehicular mobility traces track the vehicles' position over time and have been applied to bring realism to simulation tools in designing solutions for routing and mobility to VANET. However, the record of traces is subject to a low sampling rate causing spatial and temporal gaps (i.e., the time interval or distances between two consecutive entries of a vehicle in the trace is large). Consequently, spatial and temporal gaps lead to network topologies that differ from reality. To overcome this problem, the authors in [Silva et al., 2015] have worked to fill these gaps in the original traces publicly available, leading to more fine-grained traces, called calibrated traces[1].

The method for filling the gap in [Silva et al., 2015] is a cluster-based solution divided into two stages. In the first one, a clustering algorithm is applied to vehicles' historical traces, and the centroid of each cluster is obtained to compose a reference system. In the second stage, the calibration is performed using a geometric-based approach. More specifically, when a gap is found in a trajectory, the reference system containing the region of the gap is obtained. Then, it selects the centroid points between the endpoints of the geometrically closed gaps. Finally, these points are incorporated into the trajectory. More details about this method are in Silva et al. [2015].

4.3.3 Working Day Model

The working day model mobility model defines the node's mobility according to three major activities the nodes can do. They are at home, working and doing some evening activities with friends. These activities are the most common and capture most of a working day for most people Ekman et al. [2008]. The activities differ from each other. These submodels repeat every day, resulting in periodic, repetitive movement. Their configuration allows fine-tuning the model to meet the needs of the target scenarios. Communities and social relationships are formed when nodes do the same activity in the exact location.

Nodes are doing the activities daily, starting from home in the morning. Each node is assigned a wakeup time, determining when the node should start from home. The node uses the same wakeup time every morning during the whole simulation. The variance in the wakeup time models the differences in rhythms in real life. At wake-up time, nodes leave their homes and use different transport methods to travel to work. Nodes travel between activities by car or bus, which are different submodels. The working time is configurable. After the working hours, the nodes decide, by drawing, whether they go out for the evening activity or return home. Different user groups have different locations where the activities take place Ekman et al. [2008].

Based on this model, we generate the mobility of 2.000 people taking different transport types such as cars, buses, and taxis. These people move to 3 different districts (home, work, and leisure points) every day for one week. The traffic simulation is made on The ONE simulator, using the parameters described in Table 4.1.

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[1] For more information about the calibrated traces, visit: `www.wisemap.dcc.ufmg.br/urbanmobility`.

Parameters	**Values**
# of people	2 mil
Groups	8 groups in 3 districts
% of vehicles	50%
Places	Home, work and leisure points
Transport Type	Buses, cars and taxis
Simulator	The ONE

Table 4.1: Working Day Movement Model parameters.

4.4 Methodology

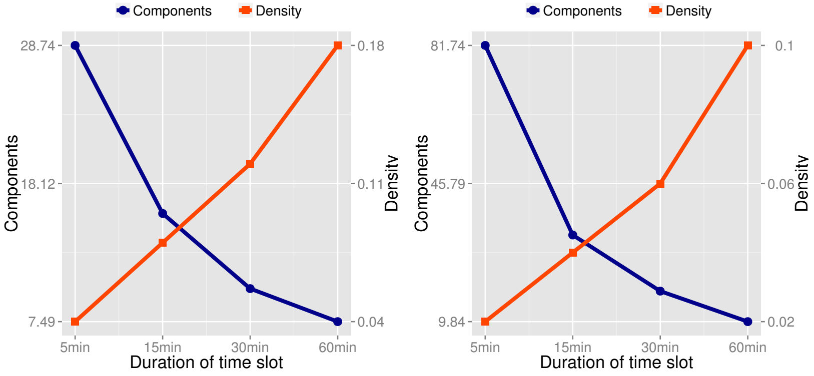
This section details the modeling used to create the temporal graph, the characteristics of the random graphs used as references in the results, and the definition of evaluated metrics used in the characterization.

4.4.1 Temporal Graphs

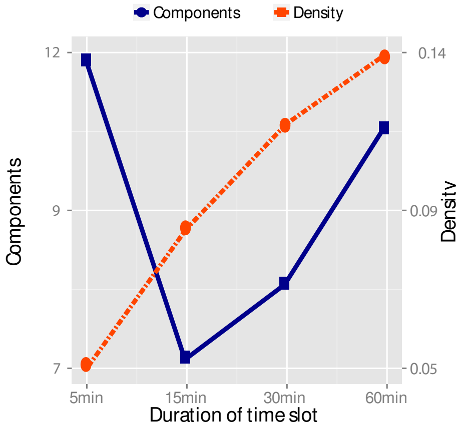
The temporal graphs are created considering the unit disc model, which allows us to infer the encounter between vehicles, i.e., when two vehicles are within communication range. In our evaluation, we consider the communication ranges of 100 m, according to the protocol 802.11p.

Then, we map the vehicle's mobility and encounters described in the trace into a temporal graph. Figure 4.1 shows the number of components and the edge density to the graph when we range the time slot duration. As we can see, a concise time slot implies a fragmented network, presenting many nodes without connections and a low-density graph. On the other hand, a long time slot generates a small number of components and a higher-density graph, which portrays a homogeneous behavior in the metrics. Thus, we divide the whole trace into discrete time slots of duration $t = 15\ min$, aiming to capture the traffic changes better. We generate each temporal graph $G(t)$ using the Growing Time Window technique [Hossmann et al., 2010], which combines all the encounters during the same time slot.

The temporal graph at the time t is an undirected graph and can be formally defined as a graph $G(t) = (V, E)$, where V represents the set with all vehicles v_i and E represents the set of edges e_{ij}. In $G(t)$, an edge $e_{ij}(t)$ exists between the vehicles v_i and v_j during time t, with $i \neq j$. The evaluation of each metric is applied in each graph, considering each temporal graph



(a) Rome (b) San Francisco



(c) Helsinque

Figure 4.1: Number of Components and Edge Density varying time slot window for 100 meters of communication range.

$G(t)$. Thus, we intend to analyze the encounters in each period t. For each trace, 96 graphs are generated describing the vehicles encounters per day $G(t) = \{G(t_1), G(t_2), G(t_3), ..., G(t_{96})\}$, and the value of the final metrics represent the average for each metric in each time slot analyzed. Also, we compare the results with random graphs G^R generated with the same degree distribution $G^R(t) = \{G^R(t_1), G^R(t_2), G^R(t_3), ..., G^R(t_{96})\}$.

4.4.2 Random Graphs

A random graph G^R is obtained from a vertex set and its respective degree distribution. The criteria to add an edge between two vertexes in the graph G^R is made randomly, based on probabilities models. In this work, the model used to add edges uses an urn algorithm that creates random structures [Johnson and Kotz, 1977]. In this algorithm, the first step is to insert d_i *balls* in an urn, marked with the identifier i of the vertex. The amount of *balls* of each vertex equals the degree of the vertex i. The total amount of *balls* in the insertion process in the urn matches with the degree distribution of the original graph G. Since this step, two *balls* b_i and b_j are randomly selected, and their identifiers are compared. If $I \neq j$ has no edges between this vertex, an edge e_{ij}, is added. The selection step is made until there is no *ball* inside the urn, or there is no possibility to add more edges in the graph, according to the insertion criteria. In this work, for each temporal graph $G(t)$, we generated its random graph G^R, where the metrics are computed.

4.4.3 Complex Networks Metrics Evaluated

Below, the social metrics chosen for this evaluation will be described considering the aspects and characteristics of the mobility of vehicles. As for vehicle mobility, we classify these metrics in macroscopic and microscopic metrics [Uppoor and Fiore, 2012]. The macroscopic metrics represent the network's global state, which can portray all vehicles' general behavior and the temporal graph's evolution. The microscopic metrics define individual values for the vehicle representing the behavior of a unique vehicle. We select as macroscopic metrics the Distance, Density, and Edge Persistence, and as microscopic metrics, we select the Node Degree, Cluster Coefficient, and Topological Overlap.

Macroscopic Metrics:

Distance: This metric comprises the length of a path between a pair of vehicles regarding the number of hops. In VANETs, the distance can represent common interests among the drivers. If the distance between the vehicles v_i and v_j is high, they are physically separated and probably do not visit nearby places. Otherwise, if the distance is small, v_i and v_j may tend to visit close places or have congruent trajectories. Generally, graphs with small-world behavior have small distances.

Density: Represents how dense the network is, i.e., the number of connections between the vehicles. In the context of VANETs, urban regions can have higher densities than rural areas. This is particularly correct in the downtown region, where the traffic is slow, and there are traffic jams. This metric computes the ratio between the number of existing edges $e(t)$ in the graph and the number of edges of a complete graph $|V||V-1|/2$.

Edge persistence: is a metric that represents the persistence of an encounter among two vehicles. This analysis considers edge persistence as the number of times the vehicles v_i and v_j encounter over time. We compute this metric in the edge weight function, representing the number of times this encounters $e_{ij}(t)$ happens.

Microscopic Metrics

Node Degree: determines the number of distinct encounters a vehicle has during a period. The trajectory and the period of the day can influence this metric. If a vehicle passes through a region with higher density traffic or in a rush hour, its degree tends to be high. On the other hand, its degree can be low or null in regions far from the downtown or in hours with low traffic. As a formal definition, a vehicle v_i at time t is defined by: $Degree_i(t) = ||\{v_j | \exists e_{ij}(t)\}||$.

Betweenness: This metric indicates the node's centrality in a network. This computation corresponds to the shortest paths from all vertices to all others that pass through that node. A node that presents high betweenness has a significant influence on the network.

Cluster Coefficient: This metric evaluates how close the neighbors of a vehicle v_i are in the graph, i.e., the probability that two neighbors of v_i have already met. This metric can represent regions with traffic jams, describing a high cluster coefficient. Besides, if the network presents the small world phenomenon, its cluster coefficient will also be elevated Watts and Strogatz [1998].

Topological Overlap: This metric portrays the graph's similarity of contacts among the vehicles. We can define the topological overlap $to(v_i, v_j)$ of a pair of vehicles v_i and v_j as the ratio of neighbors shared by two vehicles. Equation 4.1 formally defines the topological overlap between the vehicles v_i and v_j.

$$to(v_i, v_j) = \frac{|\{k|(v_i, v_k) \in E_t\} \cap \{k|(v_j, k) \in E_t\}|}{|\{k|(v_i, k) \in E_t\} \cup \{k|(v_j, k) \in E_t\}|} \tag{4.1}$$

4.5 Numerical results

In this Section, we present the numerical results of the interaction characterization. This analysis was executed considering the traffic variation during the day and week. The focus is to identify behaviors and proprieties that describe the routines and characterize the interactions in vehicular networks. We analyzed Rome and San Francisco's real calibrated traces and Helsinki's Trace, generated by the working day model, according to the methodology defined in Section 4.4. We present the traffic evolution and the results according to metrics and properties described in Section 4.4.3.

4.5.1 Traffic Evolution

This Section presents the traffic evolution for all traces along the day and week. In Figure 3.4, we can see the values of Rome, San Francisco, and Helsinki's Trace. Comparing the weekdays and the weekends, we observed that the difference between these days in Rome (Fig. 4.2-(b)) is higher than in San Francisco (Fig. 4.2-(d)). We believe that this behavior happens due to local features. We can also note a variation over the daybreak when the trip demand reduces.

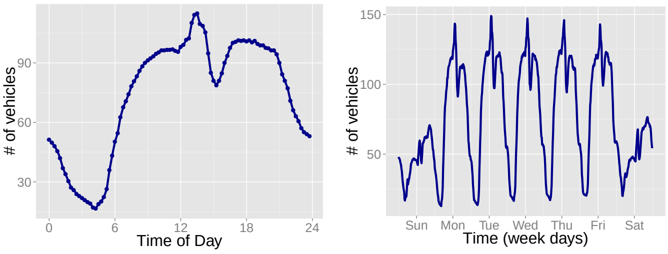
In Helsinki, Figure 4.2-(e) and (f), we highlight the presence of rush hours on weekdays, i.e., periods with higher traffic in contrast to the taxi's traces. The traffic follows the routine of people defined by the working day model. Also, the model does not present traffic during weekends because these are days off.

4.5.2 Vehicles vs. Neighbors

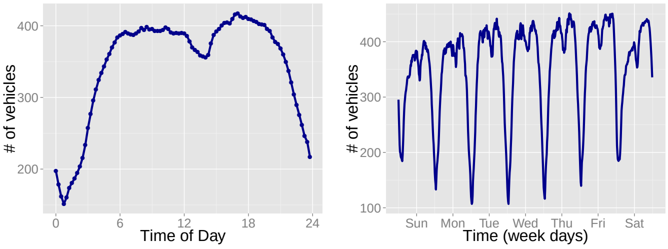
Aiming to evaluate features on interactions among the vehicles and their neighbors, we compute the metrics node degree and community. The node degree represents the number of vehicle interactions during the slot time window. Figure 4.3 shows the daily mean degree evolution for the three datasets, considering the communication range variation. In Rome, Figure 4.3-(a), we note a decrease in the degree during daybreak and, at 6 am., the value starts to increase, following the beginning of the day. This happens because during the daybreak, the number of trips surfers a reduction. In San Francisco, Figure 4.3-(b), we observe an increase in the degree at 6 am., following the beginning of the day. Moreover, during lunchtime (after 12 pm. to 2 pm.), the value of the degree presents a high increase. We attribute this behavior because, at this time, people tend to go to the same places (bars, coffee places, restaurants, etc.), and the traffic is heavy in some regions.

In Helsinki, Figure 4.3-(c), we observe a consistent behavior in the curves, with the mean degree close to 8. Also, we note an increase of 6pm, generated by the rush hours and traffic jams. Comparing the communication range variation, we observe the exact behavior of the curves in all traces, just a shift on the axis in the lines.

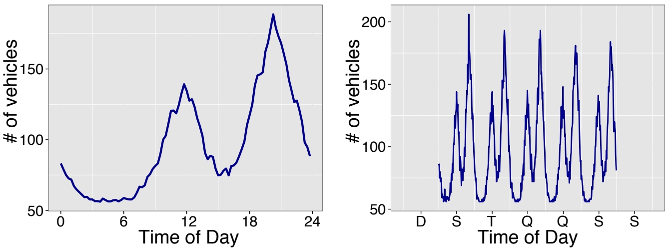
Understanding the topology of the graphs, in Figure 4.4, we generate both graphs (temporal and random) of each trace on a typical Friday at 6 pm. In each graph, we use the *walktrap community detection algorithm* to identify the communities [Orman and Labatut, 2009], highlighting the communities. We can observe, comparing the real and random graphs, the presence of communities in the real graph (nodes with the same color)—all graphs, at this



(a) Rome daily (b) Rome weekly



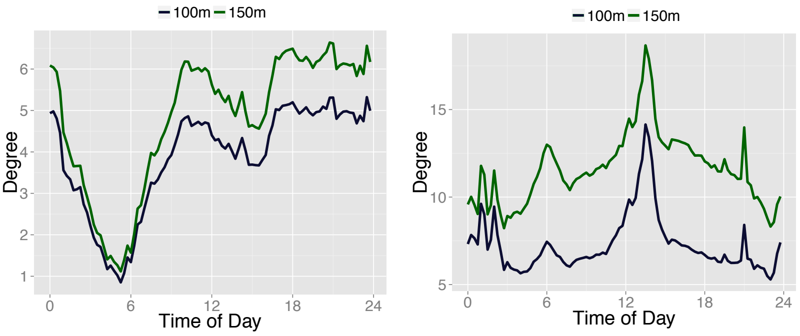
(c) San Francisco daily (d) San Francisco weekly



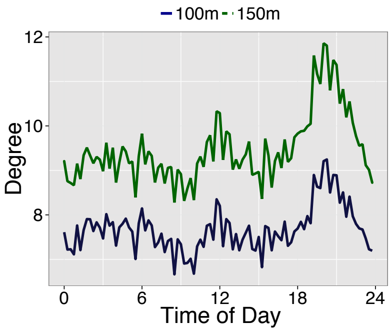
(e) Helsinki daily (f) Helsinki weekly

Figure 4.2: Traffic evolution over the day and week, in two cities: Rome and San Francisco

time, present nodes with the same interest. Also, we can observe more disconnected communities because San Francisco has more taxis. Considering the presence of communities, we can use this metric to design new services or to reach a specific community, e.g., to perform marketing and publicity or to deliver an alert message that matters only to the group.



(a) Rome
(b) San Francisco

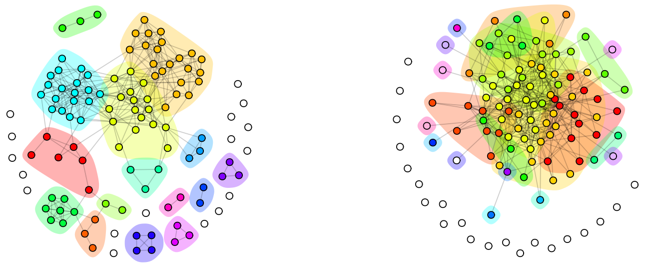


(c) Helsinki

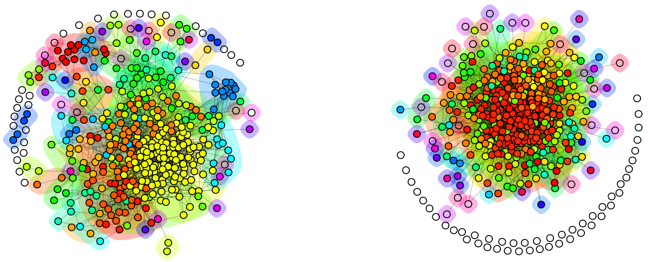
Figure 4.3: Degree daily evolution for Rome, San Francisco, and Helsinki's traces, varying the communication range.

4.5.3 Centrality

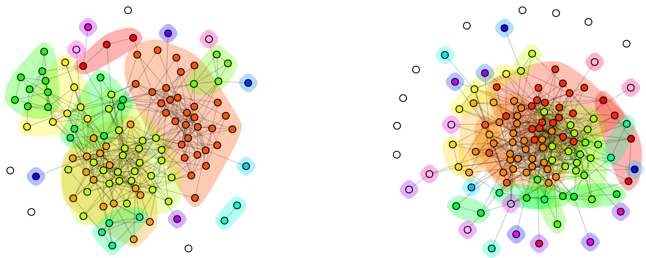
Analyzing the centrality of the vehicles in the network, Figure 4.5 presents the results of the mean of betweenness to all traces. Considering the criteria to add an edge to the original graph, we can observe that the random graphs reduce this value, which proves that random graphs remove the features of the original graphs. Also, we observe that in the San Francisco trace (Fig. 4.5-(b)), the difference among the graphs is more significant than in Rome (Fig. 4.5-(a)). This happens because, in San Francisco, more vehicles are transiting in small areas (Financial District). Besides, in Helsinki (Fig. 4.5-(c)), the lines present constant behavior because, in this trace, we have more clusters, and the vehicles are transiting in the same areas. Again, the random graphs reduce the betweenness values compared to the original graphs. This happens because the random graphs break the structure of the original graphs.



(a) Rome - $G(t)$ (b) Rome - G^R



(c) San Francisco - $G(t)$ (d) San Francisco - G^R

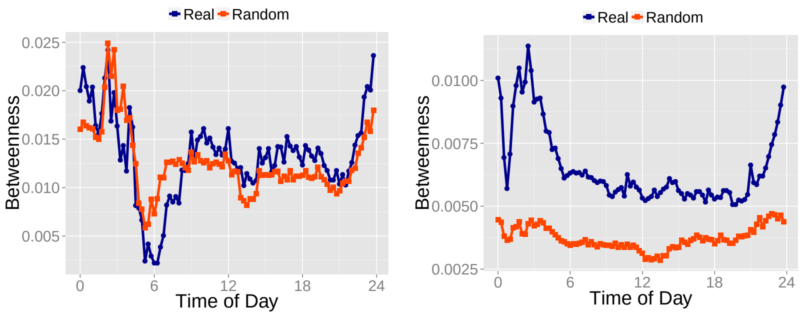


(e) Helsinki - $G(t)$ (f) Helsinki - G^R

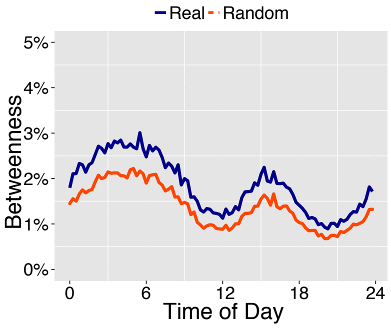
Figure 4.4: Snapshot for $G(t)$ and G^R for Rome, San Francisco and Helsinki's traces at $6pm$.

4.5.4 Small World Phenomenon

When we analyze the small world phenomenon in the graphs computing the distance and the clustering coefficient, the results are compared with random graphs with the same degree distribution as the original graphs. We compute the distance among the vehicles on the graph, i.e., the number of edges in the path among these nodes. We can see in Figure 4.6 the average distance for both traces during the day.



(a) Rome (b) San Francisco



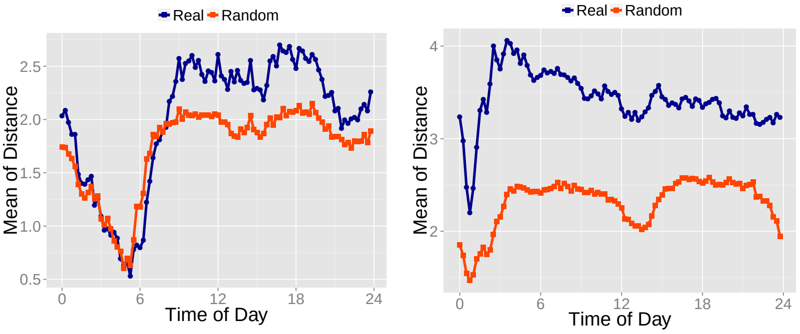
(c) Helsinki

Figure 4.5: Betweenness daily evolution for Rome, San Francisco, and Helsinki's traces.

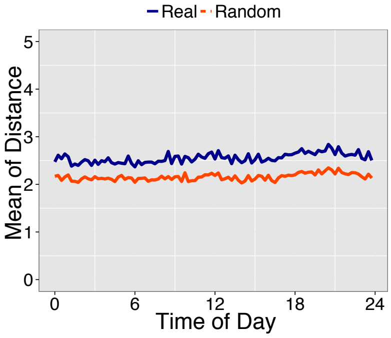
As we can see in Figures 4.6-(a), (b), (c), the mean distance for the random graphs has a lower value compared to the real traces. Due to the random criteria to add an edge in a random graph, we believe that the distance decreases with the addition of shortcuts in the graph. Moreover, for the Rome trace, Figure 4.6-(a), we note that the distance follows the traffic behavior, decreasing during the daybreak. Also, considering the number of vehicles transiting, we can observe a very short distance among them, close to 3 hops.

Regarding the San Francisco trace, Figure 4.6-(b) shows the mean distance over the day. As we can see, the distance also follows the traffic density, presenting a consistent behavior during the day, just with a reduction at daybreak. However, at 12 pm, we can see a little tendency to decrease because, at this time, the node degree increases, and more encounters happen. Considering the Helsinki trace, Figure 4.6-(c), we observe a consistent behavior during the day. This happens because these values represent the average distance, and in this trace, we have few vehicles in a short area going to the same places.

Figure 4.7 presents the results of the clustering coefficient. Remarking on this metric, we can measure how much the node neighbors are connected, forming communities in the network. Generally, the communities gather nodes that have the same interests. In vehicular networks, when two or more vehicles have the same interest, it means that they cross the



(a) Rome (b) San Francisco



(c) Helsinki

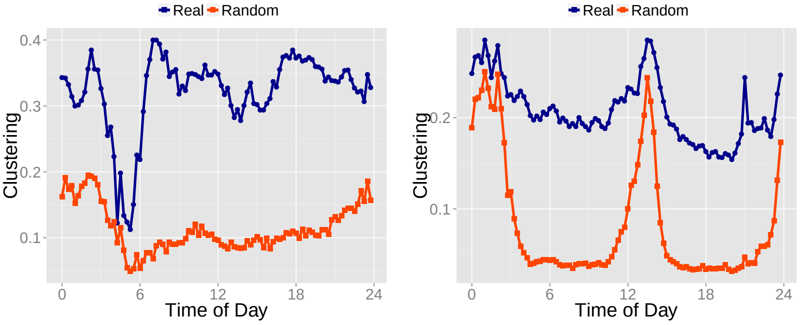
Figure 4.6: Mean Distance Daily evolution for Rome, San Francisco, and Helsinki's traces.

same roads, transit through the same area, or vehicles that interact at the same places.

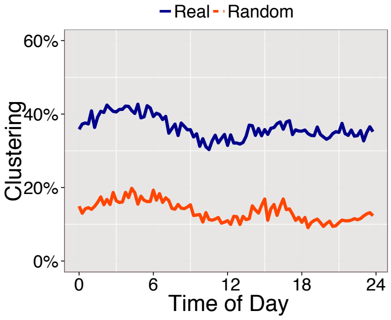
In Figure 4.7-(a), we can see the results of the Rome trace. We can note that the random graph presents an expressive difference from the real trace, which indicates that the random generation process breaks the communities from the original graph. Despite the traces that portray the taxis' mobility, the vehicles go to the same places, guided by passengers with the same interests.

In the same context, Figure 4.7-(b) shows the evolution of the clustering coefficient during the day. First, we can see that at 12 pm., the trace presents the higher value of the clustering coefficient because this is when a higher number of vehicles share the same destinations. Also, we can see during the day that although the trace portrays the taxi's behavior, where each trip represents one person's desire, they have common interests, forming vehicle communities on the graph. For different purposes, Figure 4.7-(c) presents the values to the Helsinki trace. Again, we observe consistent behavior on the lines due to the features of the trace. Beyond all, the random graph presents a result much less than the real graph, indicating structures on the graphs.

To analyze the clustering coefficient distribution among the nodes, in Figure 4.8, we present the clustering coefficient of the original traces using box plots graphics. In these



(a) Rome (b) San Francisco

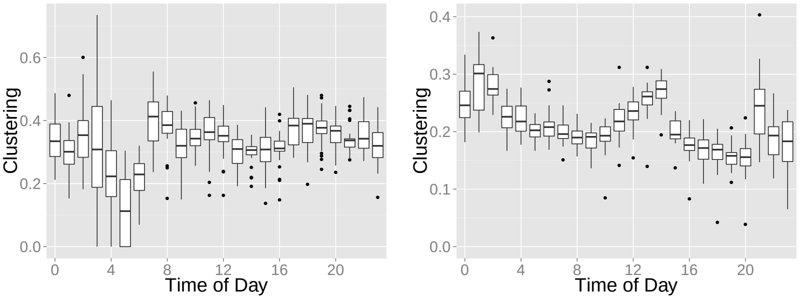


(c) Helsinki

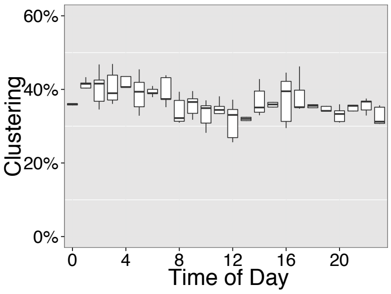
Figure 4.7: Clustering Coefficient Daily evolution for Rome, San Francisco, and Helsinki's traces.

graphics, we can see the variability of the values, the median, and the outliers for each hour during the day. To Rome trace, we can note that the trace presents a major variation in clustering values during daybreak. This is expected because, at this time, the traffic is sparse, and the destination is variable. Also, during the day, mainly during rush times, the clustering value is more constant, close to 40%.

To the San Francisco trace, the values suffer less variation, although we can see the presence of some outliers, vehicles that present different values from others. Generally, during the high-traffic period, the mean value of the clustering coefficient is close to 20%. To the Helsinki trace, we observe less variation at begin and end of the day, with values close to 40%. In the other hours, we observe more variation in the values, mainly during the vehicles' transiting days. This behavior is expected due to the trace's features, where the people go to fixed places simultaneously, forming clusters.



(a) Rome (b) San Francisco



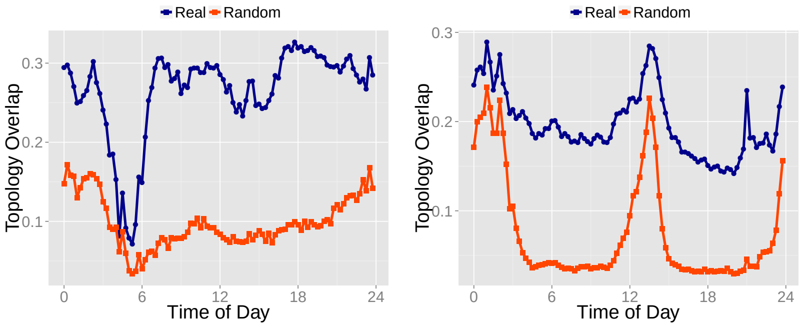
(c) Helsinki

Figure 4.8: Distribution for Clustering Coefficient for Rome, San Francisco, and Helsinki's traces.

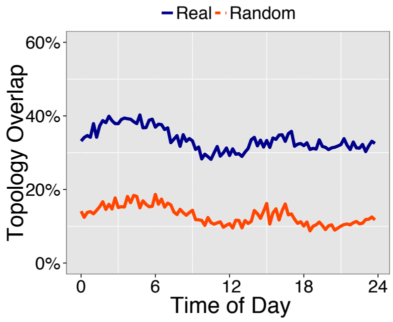
4.5.5 Similar Routines

We compute the metrics topology overlap and edge persistence to find similar behaviors on the network. These are metrics that can portray similarity on the graphs. In Figure 4.9, we present the values for the topological overlap during the day. In all traces, we observe that the random graphs present a lower value than the real traces. This behavior indicates the presence of similar interests, i.e., people go to the same places.

Regarding the Rome trace (Fig. 4.9-(a)), we see that during the day, the value of topological overlap follows the traffic density. Also, at rush times, we have more taxis sharing more neighbors, which can define similar behaviors. Considering the San Francisco trace (Fig. 4.9-(b)), we can see that the moment of the day that presents the significant value is also during lunchtime. Whether we have more taxis going to the same destinations, the probability of seeing higher values of topological overlap is more significant. For the Helsinki trace (Fig. 4.9-(c)), we also observe the difference between the original and random graphs. Moreover, we observe a higher number of familiar neighbors' vehicles, which follow the features of the trace, i.e., groups of people going to the same place. Comparing the traces, Helsinki presents more significant values than Rome and San Francisco's.



(a) Rome (b) San Francisco

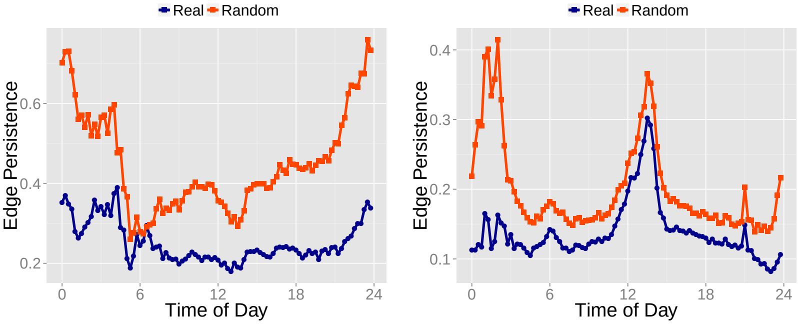


(c) Helsinki

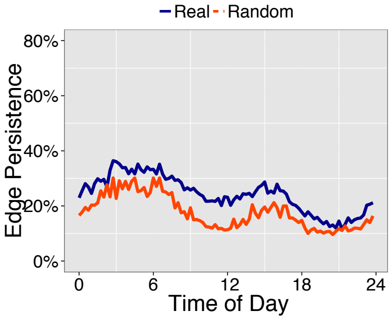
Figure 4.9: Topological Overlap Daily evolution for Rome, San Francisco, and Helsinki's traces.

We consider the contact repetitiveness in each slot time to compute the edge frequency during all days. Besides, although the random generation process, we also compute the edge persistence to random graphs. Figure 4.10 shows the results. We can note that the Rome trace (Fig. 4.10-(a)) presents a significant edge persistence than the San Francisco trace, i.e., in Rome, the edges are repeated on average 30% over the day, compared with San Francisco is 10% of repetitiveness. Also, in the San Francisco trace, Figure 4.10-(b), the greatest value of edge persistence is 30%, which is observed at lunchtime when we have more trips with familiar destinations. This happens because people can go to the same place but not take the same taxi. However, in both taxi traces, the frequency value of random graphs is more significant than the original traces, which represent the features of this type of vehicle.

In contrast, in Helsinki trace (Fig. 4.10-(c)), the vehicles present a significant value to persistence in rush hours close to 40%, characterizing the people with similar behavior. Also, due to the characteristics of the working day model, this trace presents a more significant value of persistence than the random graphs, which define social behaviors in this graph.



(a) Rome (b) San Francisco



(c) Helsinki

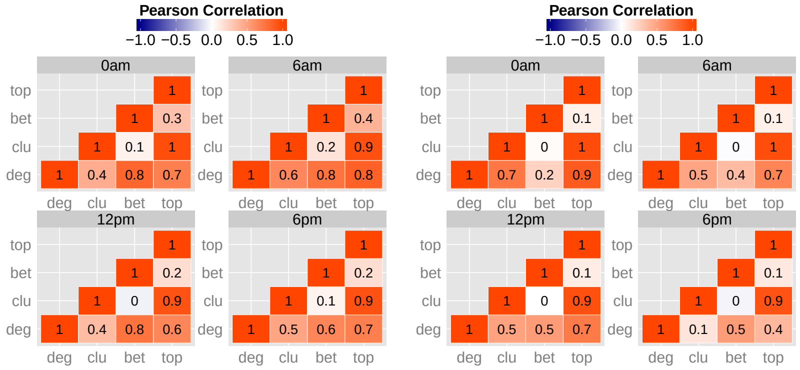
Figure 4.10: Edge Persistence Daily evolution for Rome, San Francisco, and Helsinki's traces.

4.5.6 Metrics Correlation

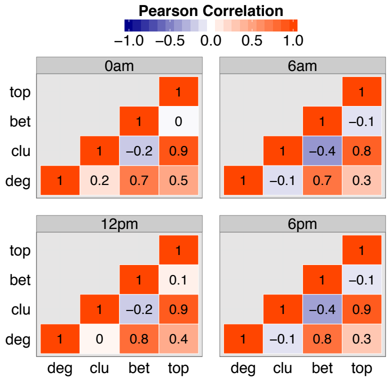
Aiming to verify the dependency level among the metrics and if metrics present the same behavior, we calculate the Pearson Correlation. This correlation defines the linear correlation between two variables. It defines the correlation level by a value ranging from -1 to 1. When the value is positive, there is a correlation, and we can define the level of correlation according to the scale: weak ($0,0$ to $\pm 0,3$), moderate ($\pm 0,3$ to $\pm 0,7$), and strong ($\pm 0,7$ to $\pm 1,0$) [Becker et al., 1988].

Figure 4.11-(a), (b), and (c) present the correlation results to the metrics topology overlap, clustering coefficient, node degree, and betweenness to all traces analyzed. We observe that the topology overlap and clustering coefficient for all datasets present a higher correlation (0.9 to 1). Both metrics portray common interests among the vehicles, which explains these results. However, the correlation of these metrics and others is low. Another value observed is the correlation between node degree and betweenness. The higher the degree of a node, the higher the likelihood of more paths crossing it; values explain the range

of the interval 0.7 a 0.9.



(a) Rome (b) San Francisco



(c) Helsinki

Figure 4.11: Grid of Pearson Correlation between the metrics.

4.6 Chapter remarks

In this chapter, we presented an analysis of the interactions in vehicular networks using two vehicular traces that describe the mobility of taxis in the metropolitan area and one trace generated by the working day model. We analyzed the San Francisco, Rome, and Helsinki traces. We could verify higher interactions of the people's routines on the vehicles' traffic for all traces. Despite San Francisco and Rome's Traces being taxi passengers, they define the places to go, and people have similar routines, which is portrayed in interactions between the traffic and the time of day, with the presence of rush times and traffic jams. We verified that they share destinations and interests, forming communities on the graph. Besides, in Helsinki, we also verified the influence of the people's desires in the traffic, with vehicles that share the same routines and behaviors.

Thus, by the work presented in [de Melo et al., 2015], we can classify the encounters in San Francisco and Rome's Trace as *acquaintance*: a group of vehicles that share many common encounters, but not meeting often, and in Helsinki's Trace as *friends*: a group of vehicles that meet each other regularly and tend to know the same people. In future works, we intend to extend this evaluation by grouping more traces that describe different mobility behaviors, such as taxis, buses, cars, and bikes. Moreover, we will use more statistical tests, tools, and techniques to define mobility models that better portray the vehicle's behaviors. Furthermore, we will use these results as input to services and protocols in vehicular networks, aiming to improve service performance and ameliorate vehicle connectivity.

CHAPTER

5

Socially Inspired Dissemination

> We cannot solve our problems
> with the same thinking we used
> when we created them.
>
> Albert Einstein

5.1 Introduction

In Vehicular Ad Hoc Networks, sending messages from a source to all vehicles inside a geographic region will be very common. Such activity is known as data dissemination, a required service by many applications. Data dissemination solutions must consider two important challenges. The first one, known as the *broadcast storm problem*, happens when a group of vehicles close to one another starts to transmit data messages at the same time, leading to a high number of message collisions and severe contention at the link layer [Tonguz et al., 2010; Schwartz et al., 2011]. The second one, known as the *intermittently connected network problem*, happens in scenarios with low traffic densities, such as daybreak, holidays, and rural areas, in which the number of vehicles is not enough to disseminate data messages using direct multi-hop communication [Viriyasitavat et al., 2011; Ros et al., 2012].

A factor that contributes to the emergence of these problems is the driver's routine. Usually, people have similar behavior, which increases the likelihood of going to the same places simultaneously. Moreover, while moving around, drivers are susceptible to speed limits, traffic lights, obstacles, etc. Therefore, it is reasonable to assume that these factors combined lead to microscopic and macroscopic traffic density variations. A better understanding of these routines and their impact on the overall traffic condition is fundamental in designing better communication protocols for VANETs. In particular, in the context of this work, for tackling the two problems faced by data dissemination solutions.

Vast research investigates the social aspects inherent to VANETs [Cunha et al., 2014a; Fiore and Härri, 2008; Loulloudes et al., 2010; Liu et al., 2012; Naboulsi and Fiore, 2013]. In summary, they show social properties encoded in these networks. With this in mind, we leverage these social aspects to design a *Socially Inspired Broadcast Data Dissemination* for VANETs. In our solution, we explore two approaches to perform data dissemination in VANETs: a delay-based solution and a probabilistic-based solution. In the delay-based solution, we use two social metrics to determine when vehicles should rebroadcast data messages. We use three social metrics in the probabilistic-based solution to determine which vehicles should rebroadcast data messages. With these solutions, we aim to increase the delivery ratio, decreasing the overall network overhead independently of the road traffic condition. Simulation results show that, when compared to three related solutions – UV-CAST [Viriyasitavat et al., 2011], ABSM [Ros et al., 2012] and AID [Bakhouya et al., 2011]– under a Manhattan grid and a city scenario based on a realistic mobility dataset, our solutions possess a higher delivery ratio, decrease both the number of collisions and the total number of data messages transmitted, and they also have an acceptable delay.

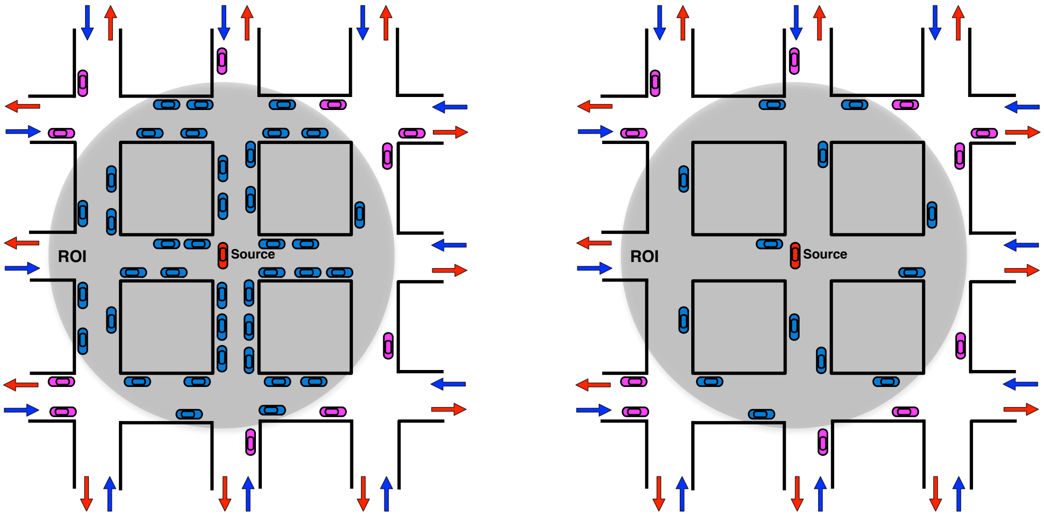
The remainder of this chapter is organized as follows. Section 5.2 presents the definition of data dissemination and an overview of the recent related work. Section 5.3 discusses how social metrics can help improve communication protocols for VANETs. Section 5.4 presents our two socially inspired solutions. Section 5.5 describes the simulation scenarios and the metrics and presents the simulation results. Finally, Section 5.6 presents our final remarks.

5.2 Data Dissemination

Many vehicular applications use the data dissemination process to deliver the message and provide their services. However, each application has specific requirements, which demand different strategies to promote data dissemination. In this section, we present more details about the data dissemination process (Section 5.2.1) and a state-of-the-art review (Section 5.2.2).

5.2.1 Definition

Data dissemination corresponds to the process in which a single source vehicle or roadside unit broadcasts data messages to all vehicles located inside a region of interest (ROI) through multi-hop communications, as illustrated in Figure 5.1. The ROI is defined by the application for which the messages must be disseminated. Moreover, in this work, for the sake of simplicity, we assume the ROI is defined as a circular region centered at the source. However, any region may be employed as long as a vehicle can determine whether it is inside such a region. The main goal of this process is to guarantee message delivery to all vehicles inside the ROI independently of the road traffic condition. Moreover, according to application requirements, the data dissemination process can know other metrics, such as delay, collisions, and overhead. Therefore, the solution must be able to operate under both dense (Figure 5.1(a)) and sparse (Figure 5.1(b)) scenarios, which requires tackling the broadcast storm and intermittently connected network problems.



(a) Dense traffic (b) Sparse traffic

Figure 5.1: Data dissemination to a group of vehicles under both dense and sparse traffic scenarios [Cunha et al., 2014b].

5.2.2 State of the Art

The study looks at computer networks as social networks have increased. In literature, we can find much research that uses properties and characteristics to improve the performance of protocols and services in computer networks [Daly and Haahr, 2007; Drabkin et al., 2011; Hossmann et al., 2010; Katsaros et al., 2010; Verma et al., 2011]. Specific in vehicular networks, in [Cunha et al., 2014a; Naboulsi and Fiore, 2013], the authors discuss social features and how human life can impact vehicular networks.

In the traditional ad-hoc networks, the SimBet [Daly and Haahr, 2007] uses centrality metrics and social similarity to define the probability of a node contacting the destination node. This protocol aims to find bridge nodes able to connect two communities. Thus, it is possible to increase the broadcast coverage. In a different way of our solution, in [Drabkin et al., 2011], the authors present a data dissemination protocol. This protocol defines the retransmission probability for a node to be inversely proportional to its number of neighbors. However, this protocol focuses on performing data dissemination in high-density environments.

In [Verma et al., 2011], the authors use the small world concepts to design a wireless mesh network. Due to the features and shortcomings of wireless mesh networks, such as throughput degradation and poor capacity scaling, the authors outline strategies to create shortcuts between router nodes, aiming to decrease communication delay.

However, some peculiarities in vehicular networks differ from traditional ad hoc networks. Thus, the traditional solutions proposed for mobile ad hoc networks cannot be applied directly to vehicular networks. In VANETs, vehicles portray higher speeds, which leads to many changes in the network topology and very fast contact among the vehicles. Furthermore, the traffic condition depends on the region (rural areas, highways, downtown), the period of the day (rush times and day breaks), and the weekday (workday, weekends, and holidays).

Many are the solutions explicitly proposed to vehicular networks to perform the data dissemination [Bakhouya et al., 2011; Ros et al., 2012; Schwartz et al., 2011; Tonguz et al., 2010; Villas et al., 2014; Viriyasitavat et al., 2011]. For instance, in [Tonguz et al., 2010], the authors present the DV-CAST, which aims to solve both problems (broadcast storm and network partitions). DV-CAST uses periodic beacon messages to build the local topology (one-hop neighbors) to rebroadcast a message. DV-CAST performs data dissemination in both dense and sparse networks. For this, during the data dissemination, the receiver applies the broadcast suppression algorithm if the local topology is well-connected; otherwise uses the store-carry-forward mechanism as a solution in a sparsely connected neighborhood. However, in high-mobility scenarios, the DV-CAST performance depends on the beacon frequency, whose optimal value is challenging to establish. In addition, DV-CAST focuses only on highway topologies.

Simple and Robust Dissemination (SRD) [Schwartz et al., 2011] solution was conceived to operate under dense and sparse vehicular networks and is an improvement over DV-CAST. Like DV-CAST, SRD relies exclusively on local one-hop neighbor information and does not employ any particular infrastructure. Among the main improvements, when compared to

DV-CAST, SDR proposes an *optimized slotted-1-persistence* broadcast suppression technique. Under this scheme, vehicles have different priorities to rebroadcast according to their moving direction. SRD prevents the broadcast storm problem in dense networks and deals with disconnected networks by relying on the store-carry-forward communication model. However, the SRD performs directional data dissemination in highway environments.

In [Ros et al., 2012], Ros et al. propose the ABSM. This is a solution to disseminate data in VANETs with varying road traffic conditions. The main idea of ABSM is to use the Minimum Connected Dominating Set (MCDS) concept to determine the vehicles that will forward the message during the dissemination process. Then 100 % coverage is guaranteed with low overhead. However, determining the MCDS is an NP-hard problem. Therefore, the authors define a distributed heuristic to determine whether a vehicle belongs to the MCDS. Thus, the vehicles in the MCDS are assigned a lower waiting delay to rebroadcast the message.

Moreover, aiming to guarantee message delivery in sparse scenarios, ABSM relies on periodic beacons to advertise the neighbors the presence of new vehicles around. Then, when a vehicle receives a beacon from a neighbor and does not acknowledge receipt of a message, the vehicle forwards the message to the neighbor. However, this delay-based solution is not applied to scenarios with delay-sensitive applications.

Another solution proposed to VANETs is the AID [Bakhouya et al., 2011]. This is a decentralized and adaptive solution for information dissemination in VANETs, where the vehicles decide whether or not to forward the message depending on the probability. This probability is set up based on the number of times the vehicles receive the same message in a given period. In scenarios with dense traffic, several vehicles might drop the message since it has already been forwarded by several vehicles, reducing the broadcast storm problem. However, this solution needs to deal with the problem of intermittent connections on the network.

Taking into account the design of the solution for both scenarios, the UV-CAST [Viriyasitavat et al., 2011] is proposed to perform data dissemination in different traffic conditions. Thus, the vehicles work in two states: broadcast suppression or store-carry-forward. When a vehicle receives a data message for the first time, it initially checks whether it is a border vehicle. Border vehicles are the ones that are at the edge of a connected component. Thus, the UV-CAST assumes these vehicles are more likely to meet new neighbors. If the vehicle verifies it is a border vehicle, it stores the message and carries it around until an encounter with a new neighbor is made. On the other hand, if the vehicle is not a border vehicle, it executes a broadcast suppression algorithm to rebroadcast the message.

Aiming to tackle the two common problems in dissemination in [Villas et al., 2014], Villas et al. propose a new solution to perform data dissemination in VANETs, considering both scenarios: dense and sparse networks. The DRIVE relies exclusively on local one-hop neighbor information to deliver messages in these scenarios. Based on a preference zone and the distance of the transmitter, it defines the delay in the retransmission. Also, the solution employs implicit acknowledgments to guarantee robustness in message delivery under sparse scenarios. In Table 5.1, we present a comparison of these solutions, summarizing the main features of each one.

5.3 Social Metrics applied

The use of social metrics to improve the performance of protocols and services in ad-hoc networks has received much attention from the research community. Many works in the literature describe metrics evaluation, characterization, and new services that use these metrics [Cunha et al., 2014a; Fiore and Härri, 2008; Hossmann et al., 2010; Katsaros et al., 2010; Naboulsi and Fiore, 2013]. In particular, for VANETs, protocols, and services can improve considerably when considering drivers' behavior and routines. For instance, it is possible to understand daily traffic evolution better and adapt communication protocols accordingly with such knowledge.

Below, we describe a group of social metrics and the influence of each one in data communication in VANETs. Considering the vehicle's mobility, we classify these metrics in macroscopic and microscopic metrics [Uppoor and Fiore, 2012]. The macroscopic metrics represent measures of the network's global state, which can portray the general behavior of all vehicles. The microscopic metrics define individual values for the vehicle representing the behavior of a unique vehicle. We choose Distance, Diameter, Density, and Edge Persistence for macroscopic metrics. For microscopic metrics, we select the Node Degree, the Closeness Centrality, the Cluster Coefficient, and the Topological Overlap.

5.3.1 Macroscopic metrics

Distance: This metric portrays the average number of hops for a vehicle to reach another. In many cases, it may be interesting to use the shortest routes to reduce the delay in delivering messages to intended recipients. Moreover, vehicles close to one another may share a common interest, which may help direct data dissemination flows.

Diameter: By the distance, this metric captures the significant distance between two vehicles in the graph. When analyzing the network topology, a great diameter may indicate a high communication cost to reach all vehicles due to the high number of hops.

Density: This metric represents how dense the network is, i.e., the average number

Dissemination Solution	**Forwarding Strategy**	**Architecture**	**Scenario**	**Assumptions**
DV-CAST [Tonguz et al., 2010]	Position Based, Store-Carry-Forward	V2V	Highway Scenarios	GPS and Neighbors Position Required
SRD [Schwartz et al., 2011]	Position and Distance Based, Store-Carry-Forward	V2V	Highway Scenarios	GPS and Neighbors Position Required
ABSM [Ros et al., 2012]	Position and Delay Based	V2V	Urban and Highway Scenarios	GPS Receiver Required
AID [Bakhouya et al., 2011]	Statistical Based	V2V	Urban Scenarios	–
UV-CAST [Viriyasitavat et al., 2011]	Position and Store-Carry-Forward	V2V	Urban Scenarios	GPS and Neighbors Position Required
DRIVE [Villas et al., 2014]	Position, Distance, and Timer Based	V2V	Urban and Highway Scenarios	GPS receiver and Map Required

Table 5.1: Comparison of Data Dissemination Solutions for VANETs

of connections. In the context of VANETs, urban regions can have higher densities when compared to rural areas. This is particularly true for downtown regions, where traffic is very dense. With such knowledge, data dissemination solutions can adapt to the perceived traffic condition to determine whether vehicles should operate under a broadcast suppression or a store-carry-forward state.

Edge Persistence: This metric represents the persistence of an encounter between two vehicles. In some cases, the encounter happens in the same region, which indicates similar routines between two vehicles. For various vehicular applications, to reach a given destination, vehicles can use these persistent connections as a backbone for data forwarding.

5.3.2 Microscopic metrics

Node Degree: This metric presents information about a node's local neighborhood. In multi-hop data communication solutions, neighbors are used as relays to deliver data to intended recipients. For the particular case of data dissemination protocols, a vehicle with a high degree has more excellent coverage, i.e., it can deliver messages to more vehicles at once.

Closeness Centrality: This metric measures the centrality of the vehicle according to its distance from other vehicles in the network. In VANETs, vehicles with a high closeness centrality are closer to the remaining vehicles in the network. Therefore, the dissemination can be faster when choosing these vehicles as data forwarders.

Clustering Coefficient: This metric evaluates how close a vehicle's neighbors are. Commonly, vehicles that belong to a group have similar features and behaviors, and information can be helpful for the whole cluster. Thus, considering the wireless broadcast advantage, with just one transmission from a group member, it is possible to reach the whole cluster, reducing the overall number of transmissions.

Topological Overlap: This metric measures the percentage of neighbors shared among two or more nodes. Vehicles with similar interests and behaviors tend to group in a vehicular network. Usually, they have a high percentage of shared neighbors. Thus, in a dissemination process, the vehicle with a small topological value should reach different vehicles, increasing the coverage ratio.

5.4 Socially Inspired Dissemination solutions

Many are the strategies defined to perform data dissemination in vehicular networks. These strategies must work to deliver the message to all intended vehicles in different road traffic conditions. In this section, we present two data dissemination solutions, which employ two different strategies: a Delay-based solution (Section 5.4.1) and a Probabilistic-based solution (Section 5.4.2).

5.4.1 Delay-based solutions

The main idea of a Delay-based solution is to determine which vehicles should rebroadcast a received data message and when to perform it. However, this process should happen for dense and sparse road traffic scenarios. Algorithms 1 and 2 define the main steps of this process and how the vehicle calculates a waiting delay to rebroadcast the message.

For both algorithms, we assume that vehicles store and carry each received data message for the whole period in which they are inside the ROI and that the time-to-live for the message has stayed the same. Moreover, they are equipped with a Global Positioning System (GPS) or can infer their positions through other means. Each vehicle periodically exchanges beacons with its neighbors. These beacons contain context information about the vehicle, for instance, the position and the number of neighbors (node degree). Furthermore, each beacon contains the IDs of the data messages received and carried by the vehicle. Notice that embedding the IDs of received data messages into beacons is an implicit acknowledgment mechanism. Therefore, when a vehicle receives a beacon from a neighbor, it can verify whether it possesses any data message that this neighbor has not received and then forward it accordingly.

In the following two sections, we thoroughly describe each algorithm. After that, we show how the clustering coefficient, the node degree, and the combination of both metrics can be used to turn our data dissemination solution into a Delay-based solution. Initially, we show how to estimate the clustering coefficient using only one-hop neighbor information and how to use it in the waiting delay computation. We then focus on the node degree, easily obtained through beacons. Finally, we also show how to calculate the waiting delay using a combination of both metrics.

5.4.1.1 Broadcast suppression

Under dense road traffic conditions, when a vehicle receives a data message, it must carefully decide whether to rebroadcast it or not and when to rebroadcast it to avoid redundant retransmissions and, consequently, the broadcast storm problem. Algorithm 1 shows how a vehicle proceeds when it receives a data message m.

Algorithm 1 The Broadcast Suppression Algorithm

```
Require: Data message $m$ received from neighbor $s$
 1: if Vehicle is outside the region of interest specified in $m$ or the time-to-live of $m$ expired
    then
 2:     discard $m$;
 3: end if
 4: if $m$ is not a duplicate then
 5:     add a message to the list of received messages;
 6:     insert $m$ ID in subsequent beacons;
 7:     $t \leftarrow$ calculateWaitingDelay();
 8:     schedule $rebroadcast\_timer$ for $m$ to fire up at $currentTime + t$;
 9: else
10:     if $rebroadcast\_timer$ for $m$ is scheduled then
11:         cancel $rebroadcast\_timer$ for $m$;
12:     end if
13: end if
14:
15: Event: scheduled $rebroadcast\_timer$ for $m$ expires
16: Rebroadcast $m$;
```

Initially, the vehicle verifies whether it has left the ROI or the time-to-live for the message m has expired. In such a case, the vehicle discards m (lines 1–3). Otherwise, the vehicle checks whether m is duplicated (Line 4). If it is not duplicated, the vehicle stores m in the list of received messages that are still valid. Furthermore, it will insert the ID of m into subsequent beacons until the vehicle leaves the ROI or m expires (lines 5–6). The next and most crucial step is calculating the waiting delay t to rebroadcast m (Line 7). In Algorithm 1, we omitted how this delay is calculated because it will depend on the social metric employed. For now, it is enough to know that such delay is a value in the interval $[0, T_{max}]$, where T_{max} is a configured parameter. After calculating the waiting delay, the vehicle uses it to schedule a rebroadcast for m (Line 8). Notice that, while the vehicle is scheduled to rebroadcast m if it receives a duplicate, it cancels the rebroadcast (lines 10–11), thus avoiding possible redundant retransmission. However, when the waiting delay expires and the vehicle has not received any duplicate, it rebroadcasts m (lines 15–16).

5.4.1.2 Store-carry-forward

On the other hand, when the road traffic is sparse, and the network is partitioned, vehicles must hold received data messages and use their mobility capabilities to carry the messages to different parts of the ROI. Moreover, they must be able to determine whether a vehicle has already received a data message. For the former issue, vehicles rely on the store-carry-forward communication model. For the latter, beacons are used as an implicit acknowledgment mechanism. Algorithm 2 shows how our proposed solution delivers data messages even when the network is intermittently connected.

Algorithm 2 The Store-carry-forward Algorithm

```
Require: Beacon $b$ received from neighbor $s$
 1: for all message $m$ in the list of received messages do
 2:     if $m$ is not acknowledged in $b$ then
 3:         $t \leftarrow$ calculateWaitingDelay();
 4:         schedule $rebroadcast\_timer$ for $m$ to fire up at $currentTime + t$;
 5:     end if
 6: end for
 7:
 8: Event: data message $m$ received from neighbor $s$
 9: if $m$ is a duplicate then
10:     if $rebroadcast\_timer$ for $m$ is scheduled then
11:         cancel $rebroadcast\_timer$ for $m$;
12:     end if
13: end if
14:
15: Event: scheduled $rebroadcast\_timer$ for $m$ expires
16: Rebroadcast $m$;
```

When a vehicle receives a beacon b from a neighbor s, it verifies whether a data message has not been acknowledged by s in b (lines 1–2). For that, the vehicle looks into its list of received messages and compares their IDs with those contained in b. If the vehicle finds any message m that has not been acknowledged, it calculates a waiting delay t to rebroadcast m (Line 3). Once again, such delay will depend on the social metric employed. After calculating the waiting delay, the vehicle schedules to rebroadcast m with delay t (Line 4). As in the broadcast suppression algorithm, while the vehicle is scheduled to rebroadcast m if it receives a duplicate, it cancels the rebroadcast (lines 9–12), thus avoiding possible redundant retransmission. However, when the waiting delay expires and the vehicle has not received any duplicate, it rebroadcasts m (lines 15–16).

By using these two algorithms in conjunction, our proposed solution can tackle both the broadcast storm and the intermittently connected network problems. Moreover, it is worth noticing that a vehicle can be made aware of the current road traffic condition, i.e., whether the network is dense or sparse. In either case, the vehicle always tries to avoid redundant retransmissions and increase the message delivery capability to intended recipients.

5.4.1.3 Clustering Coefficient solution

The clustering coefficient for a vehicle v is the number of connections between neighbors of v divided by the total number of possible connections between neighbors of v [Watts and Strogatz, 1998]. Therefore, to accurately calculate the clustering coefficient for vehicle v, it is necessary to know the two-hop neighborhood knowledge of v. Given that VANETs are highly dynamic networks and obtaining such knowledge can be cumbersome, we use position information to estimate the clustering coefficient, particularly to determine whether a vehicle's two neighbors are connected. As already stated, each vehicle knows the position of each neighbor due to the received beacons. Therefore, to verify whether two neighbors are connected, vehicle v must only check whether the distance between these two neighbors is below the estimated communication range. After that, v can calculate its estimated clustering coefficient.

With its own estimated clustering coefficient, a vehicle v can calculate its waiting delay to rebroadcast. According to an analysis of the estimated clustering coefficient concerning the vehicle density (see Figure 5.3 and 5.4), for lower densities, the clustering coefficient is also low, but the variability is high. On the other hand, when the density is high, also is the value for the estimated clustering coefficient, but the variability is low. For our purposes, the greater the variability, the better. Otherwise, we risk assigning the same or similar waiting delay to all vehicles. Therefore, for this first proposal, we give a higher priority to rebroadcasting for vehicles that have a low estimated clustering coefficient. In other words, the lower the estimated clustering coefficient, the lower the waiting delay. Equation 5.1 shows how the waiting delay is calculated using this metric, where the value for *estimatedCC* ranges in the interval [0, 1].

$$t = T_{max} \times estimatedCC \tag{5.1}$$

5.4.1.4 Node Degree solution

When we look into the analysis of the node degree (see Figure 5.3 and 5.4), we can see that when the vehicle density is low, the degree and its variability are also low. However, when the density increases, both the degree and its variability increase. Therefore, we use an opposite approach based on the node degree in the proposal. The higher the degree of a vehicle in a given neighborhood, the higher its priority to rebroadcast the message, i.e., the lower the waiting delay. Each vehicle will know its max neighbor degree due to the *degree* information in the received beacons. Equation 5.2 shows how the waiting delay is calculated using this approach. Here, *degree* is the degree of the vehicle that is calculating the waiting delay, and *maxDegree* is the maximum between *degree* and the highest degree among all neighbors of the vehicle.

$$t = T_{max} \times \left(1 - \left(\frac{degree}{maxDegree}\right)\right) \tag{5.2}$$

5.4.1.5 Joint solution

Here, we also propose a joint solution, i.e., one that uses both the estimated clustering coefficient and the node degree. Assuming that a single metric may not be adequate for all traffic density scenarios, combining the two may produce better results. Equation 5.3 shows how this joint solution can calculate the waiting delay. As observed, each metric contributes to a fraction of the total waiting delay, controlled by the factors α and β. To balance the delay equation, we assume that $\alpha = \beta = 0.5$.

$$t = t_{cc} + t_{degree} \tag{5.3}$$

$$t_{cc} = \alpha T_{max} \times estimatedCC \tag{5.4}$$

$$t_{degree} = \beta T_{max} \times \left(1 - \left(\frac{degree}{maxDegree}\right)\right) \tag{5.5}$$

5.4.2 Probabilistic-based solutions

Another strategy to perform the data dissemination is using a Probabilistic-based approach. The main idea is determining which vehicles should rebroadcast the data message received probabilistically. This process is made by deriving a probability for each node based on its social metrics. We assume that in this solution, the advertisement beacon mechanism works the same way as in the Delay-based solution (see Section 5.4.1). Algorithms 3 and 4 define the main steps of the probability computation process. In the following two sections, we thoroughly describe each algorithm. Next, we describe the two ways to define the probability. Firstly, the probability is defined based on the joint metrics node degree and clustering coefficient. Second, the probability is defined considering the metric topological overlap.

5.4.2.1 Broadcast suppression

Aiming to deal with the broadcast storm problem, when a vehicle receives a data message, it must decide whether to rebroadcast it, avoiding redundant retransmissions. The Algorithm 3 shows the steps executed when a vehicle receives a data message m.

Initially, the vehicle verifies whether it is outside the ROI or the time-to-live message m expires. The message m is discarded (Lines 1–3). However, it verifies whether the message is duplicated (Line 4). If it is not duplicated, the vehicle stores m in the list of received messages that are still valid. Then, it inserts the ID of m into the next beacons while it is inside the ROI or the time-to-live of m does not expire (Lines 5–6). Next, the vehicle calculates the probability of rebroadcasting m (Line 7), which depends on the chosen metric. The two ways to define the probability are presented in the next sections 5.4.2.3 and 5.4.2.4. After, it generates a random value between 0 and 1 and rebroadcasts the message m if the random value is less or equal to p (Lines 8–10). If the vehicle receives the same message m while the rebroadcast is scheduled, it cancels the rebroadcast (Lines 13–14), reducing the number of redundant retransmissions and collisions (Lines 18–19). Then, following the algorithm, the vehicle rebroadcasts the message when the schedule timer expires.

Algorithm 3 The Broadcast Suppression Algorithm

```
Require: Data message $m$ received from neighbor $s$
if vehicle is outside the region of interest specified in $m$ or the time-to-live of $m$ expired then
    discard $m$;
end if
if $m$ is not a duplicate then
    add a message to the list of received messages;
    insert $m$ ID in subsequent beacons;
    $p \leftarrow$ calculateTransmissionProbability();
    $random \leftarrow$ choose a random number between 0 and 1;
    if $random \leq p$ then
        schedule the $rebroadcast$ for $m$;
    end if
else
    if $rebroadcast$ for $m$ is scheduled then
        cancel $rebroadcast$ for $m$;
    end if
end if

Event: scheduled $rebroadcast$ for $m$ expires
Rebroadcast $m$;
```

5.4.2.2 Store-carry-forward

In the other scenario, when the traffic density is low, and the network presents partitions, the vehicles need to hold the received data message to carry it to different parts of the ROI. In the same way as the delay solution, the vehicles need to determine whether a vehicle has already received a data message. Thus, they implement a store-carry-forward communication model. The Algorithm 4 presents the steps executed when the network is intermittently connected.

When a vehicle receives a beacon b from a neighbor s, it verifies whether some data message is not acknowledged by the neighbor s in beacon b (Lines 1–2). For each message without an acknowledgment, the vehicle calculates the probability to rebroadcast and schedules the rebroadcast. Again, this probability will be defined according to the metric chosen (Line 3). More details about this computation are described in Sections 5.4.2.3 and 5.4.2.4. Following, it chooses a random value between 0 and 1, verifying if this $random$ value is less than or equal to the probability p. Then, the vehicle rebroadcasts the message (Lines 4–8). If, during this process, the vehicle overhears a retransmission of the scheduled message from some other neighbor, it cancels the rebroadcast (Lines 12–15), which contributes to reducing the number of redundant retransmissions. Otherwise, it rebroadcasts the message (Lines

Algorithm 4 The Store-carry-forward Algorithm

```
Require: Beacon $b$ received from neighbor $s$
 1: for all message $m$ in the list of received messages do
 2:     if $m$ is not acknowledged in $b$ then
 3:         $p \leftarrow$ calculateTransmissionProbability();
 4:         $random \leftarrow$ choose a random number between 0 and 1;
 5:         if $random \leq p$ then
 6:             schedule the $rebroadcast$ for $m$;
 7:         end if
 8:     end if
 9: end for
10:
11: Event: data message $m$ received from neighbor $s$
12: if $m$ is a duplicate then
13:     if $rebroadcast$ for $m$ is scheduled then
14:         cancel $rebroadcast$ for $m$;
15:     end if
16: end if
17:
18: Event: scheduled $rebroadcast$ for $m$ expires
19: Rebroadcast $m$;
```

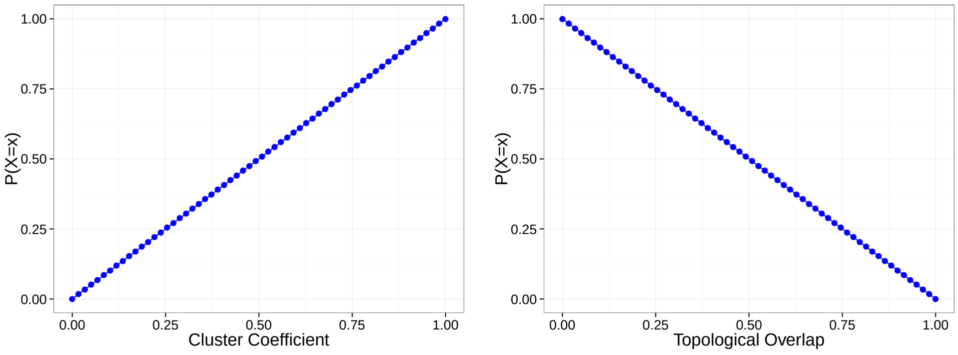
18–19).

5.4.2.3 Node Degree and Clustering Coefficient solution

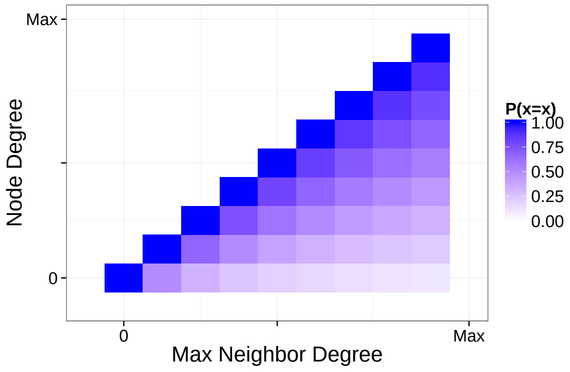
The probability definition given by the joint solution considers the metrics clustering coefficient and node degree. The focus is to favor vehicles with higher degrees and clustering coefficients. Then, the probability is defined in the following way: $prob = \alpha prob1 + \beta prob2$. Each metric will contribute to generating the final value. Thus, to balance equally, we choose the value 0.5 for variables α and β.

The value of $prob1$ is given by the metric clustering coefficient, which portrays how much the vehicles are clustered, i.e., physically close. In the context of the VANETs, this metric defines a group of vehicles that simultaneously transit in the same streets. Vehicles with higher values have more probability of forwarding the data message, increasing the broadcast coverage. In Figure 5.2-(a), we can see the probability for different values of this metric. As we can see, considering the clustering coefficient (Figure 5.2-(a)), the retransmission probability value $prob1$ is equal to the clustering coefficient, where the value also ranges between the interval [0,1].

The computation of the probability Equation 5.6 gives $prob2$, where the probabil-



(a) Clustering Coefficient (b) Topological Overlap



(c) Node Degree

Figure 5.2: Forwarding probability for each metric.

ity is defined by the ratio of the node degree and the highest degree value in the vehicle's neighborhood. The node degree depicts the number of neighbor vehicles, i.e., the number of vehicles reached by one-hop of communication. Vehicles with higher degrees are more likely to forward the data message; their transmissions will reach more vehicles. Thus, each vehicle sends its degree value into the beacons to perform this computation. Figure 5.2-(c) shows the probability for different degree and max neighbor degree values. It is possible to see that the $prob2$ favors the vehicles which present the max degree to rebroadcast the data message, increasing the transmission coverage.

$$prob2 = \frac{degree}{maxDegree} \tag{5.6}$$

5.4.2.4 Topological Overlap solution

The Topological Overlap of a vehicle v defines the ratio of neighbors that v shares with its neighbors, i.e., the fraction of common neighbors among the vehicles. Normally, these vehicles are connected, forming a group of vehicles that share interests. The Equation 5.7 presents the computation of the Topological Overlap $to_{(i,j)}$, to a pair of vehicles i and j, defining the ratio of neighbors vehicles shared by them [Vaz de Melo et al., 2013].

$$to_{(i,j)} = \frac{|\{k|(i,k) \in E_t\} \cap \{k|(j,k) \in E_t\}|}{|\{k|(i,k) \in E_t\} \cup \{k|(j,k) \in E_t\}|} \tag{5.7}$$

In this way, aiming to compute this metric, each vehicle will send its ID and neighbors' information together into the beacon messages. The key idea in choosing this metric is to increase the data dissemination coverage by selecting vehicles with few neighbors. As shown in Figure 5.2-(b), the smaller the value of a vehicle's topological overlap, the greater the probability of rebroadcast. The focus is to choose vehicles that share few neighbors to forward the data message, increasing the dissemination coverage. Thus, the probability is defined by the equation: $prob = 1 - Topology$ to favor the vehicles with low values, i.e., vehicles that do not share neighbors.

5.5 Performance evaluation

To evaluate our proposed approaches, we executed a group of simulations using OMNeT++ 4.2.2. network simulator Varga and Hornig [2008]. In all results, we compare our proposals to state-of-the-art solutions found in the literature, where two are delay-based solutions (UV-CAST Viriyasitavat et al. [2011] and ABSM Ros et al. [2012]), and one is probabilistic-based (AID Bakhouya et al. [2011]). Furthermore, in the next results, we nominated the solutions as CC-Degree (joint solution) and Topology (topological overlap solution). Following, we describe the details of the simulations and the results. Section 5.5.1 shows the details about the scenarios used in the simulations, Section 5.5.2 describes the default parameters, and Section 5.5.3 describes the metrics used in our evaluation. In Section 5.5.4, we present and discuss the results for the Delay-based solutions, and in Section 5.5.5, we present the results for the Probabilistic-based solutions.

5.5.1 Scenario

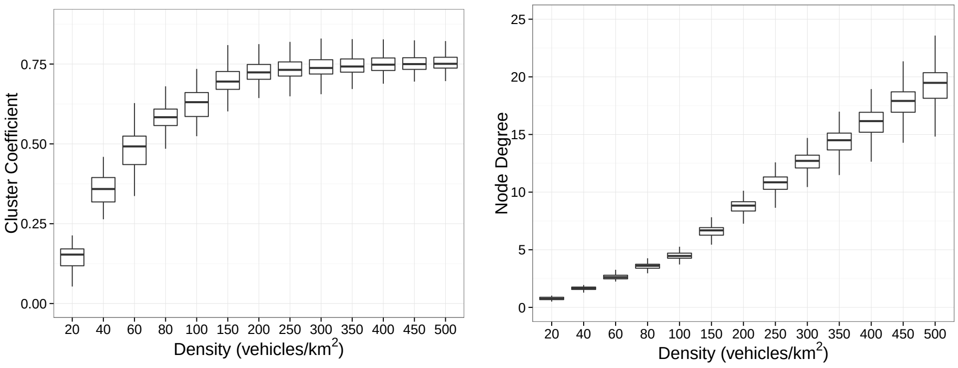
To evaluate the performance of the solutions, we used two different scenarios. One scenario favors the occurrence of the broadcast storm problem, and another favors intermittent connections and network partitions.

Manhattan scenario: This is a scenario with ten evenly-spaced double-lane streets in an area of 1 km^2. Also, we consider signal attenuation effects caused by buildings. For that, we assume that each block has an 80m × 80m obstacle, representing high-rise buildings. In order to quantify the traffic evolution in this scenario, we vary the vehicle density from 20 vehicles/km^2 to 500 vehicles/km^2. The road traffic simulation is performed by the Simulator of Urban MObility (SUMO 0.17.0) Behrisch et al. [2011]. Moreover, we positioned the source vehicle at the center of the grid, generating 100 messages of 2048 bytes to be disseminated to the whole network. The data rate is set to 1.5 Mbit/s.

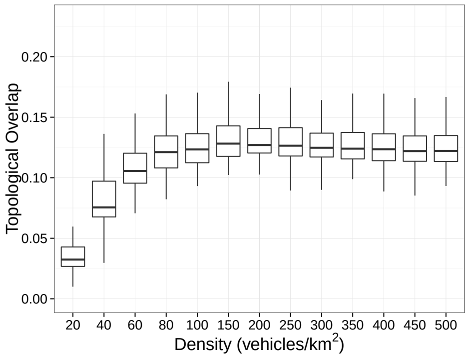
To better understand the Manhattan grid scenario, Figure 5.3 shows the estimated clustering coefficient and the node degree for the considered vehicle densities. In particular, in Figure 5.3-(a), we show the estimated cluster coefficient and its evolution. As we can see, the value for the estimated cluster coefficient under low densities is small, almost 40 %. Moreover, it has a higher variability. It happens because, for lower densities, there are few vehicles in transit. With the growth of the density, the estimated cluster coefficient increases. This is because, under higher densities, the encounter probability is also higher, and the network will be more connected. Therefore, starting at 200 vehicles/km^2, the value for the estimated clustering coefficient has a constant behavior of about 75 %. This can be explained by the fact that vehicle connections increase even if physical restrictions, such as road shapes and obstacles, constrain the network's density.

Figure 5.3-(b) presents the node degree evolution. Observing how the node degree evolves over the density variation is possible. As expected, the node degree also increases with the increase in density. For instance, at 100 vehicles/km^2, the average node degree is 5, representing that, on average, a vehicle has 5 neighbors. We also can observe that the node degree variability is higher at higher densities. In Figure 5.3-(c), we present the topological overlap evolution. The network presents low values to the metric topological at lower density because we have a sparser network. In higher densities, the topology overlap value reaches a constant value, close to 15 % of neighbors shared. In this case, we have a network more connected and a tendency to share more neighbors.

Cologne Trace: this is a realistic scenario represented by a two-hour mobility dataset covering an area of 400 km^2 over the city of Cologne, Germany Uppoor and Fiore [2012]. This trace has more details related to the physical infrastructure than the Manhattan grid, for instance, traffic light signalization, different road types, and buildings making it much more realistic. To consider different road traffic conditions, the data dissemination process is



(a) Estimated cluster coefficient (b) Node degree evolution



(c) Topological overlap

Figure 5.3: Manhattan metrics evolution.

executed at different instants of the two-hour dataset (06:30, 06:45, 07:00, 07:15, and 07:30 am.). To better understand the traffic evolution in this scenario and to facilitate comparisons with the Manhattan grid scenario, Table 5.2 shows the traffic density for each moment the dissemination is performed. As in the Manhattan grid scenario, a vehicle at the center of the network starts the dissemination. The vehicle generates 100 messages of 2048 bytes, at a data rate of 1.5 Mbit/s. The intended recipients for the dissemination are all vehicles inside an ROI with a radius of 2 km and centered at the source vehicle.

As for the Manhattan grid, Figure 5.4 shows the estimated cluster coefficient and node degree evolution for the Cologne scenario. For the estimated cluster coefficient (Fig. 5.4-(a)), we can observe a high variation for all considered times of the day. For instance, at 06:30 a.m., these values range from 0.15 to 1, where most vehicles have an estimated cluster coefficient between 0.6 and 0.9, which indicates a highly clustered network. Figure 5.4-(b) shows the node degree evolution. Once again, we can observe a high variation from 0 to 50 neighbors. These

Time (am)	**Density (vehicles/km^2)**
06:30	61
06:45	82
07:00	92
07:15	102
07:30	108

Table 5.2: Vehicle density during the time evolution for the Cologne scenario.

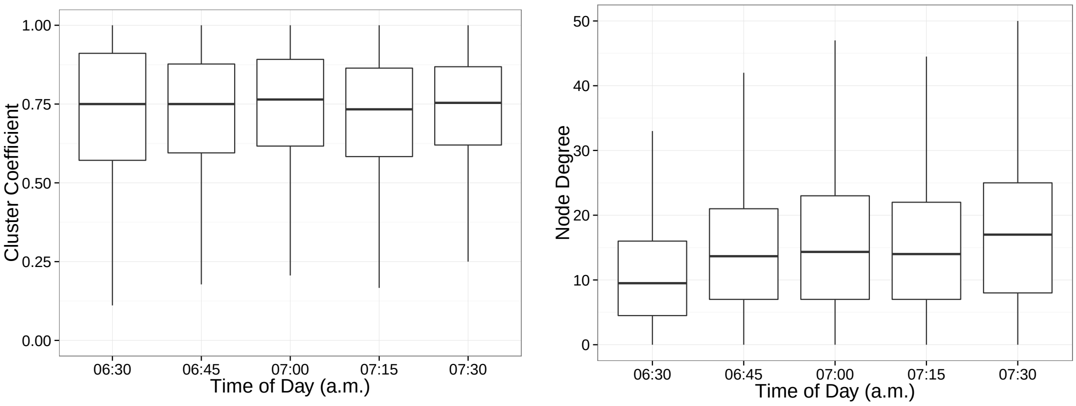
Parameter	**Value**
Transmission power	0.98 mW
Transmission range	200 m
MAC bit rate	18 Mbit/s
Maximum waiting delay (T_{max})	500 ms
Beacon frequency	1 Hz
Data message size	2048 bytes
Number of data messages produced	100
Confidence interval	95%

Table 5.3: Default simulation parameters.

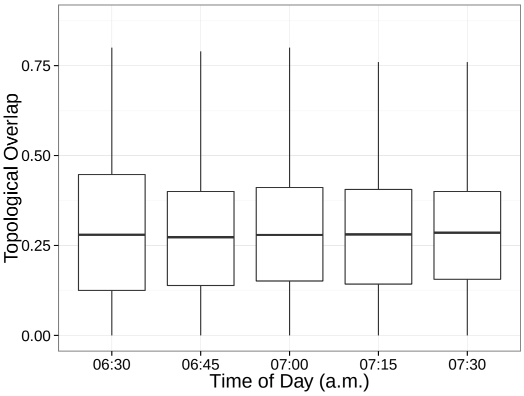
behaviors are expected due to traffic variations during rush hours. Moreover, in Figure 5.3-(c), we can see the evolution of the topological overlap. With the same behavior, we can observe a higher variation of this metric, from 0 % to 75 % of neighbors shared, and a great number of vehicles presenting 25 % of neighbors shared. This happens because, in this scenario, it represents the beginning of the day—rush hours, where the traffic is sparse with some points of density traffic.

5.5.2 Simulation parameters

We execute the OMNeT++ network simulation and the framework Veins 2.1 Sommer et al. [2011], specific to vehicular networks. We focus on improving the quality of the following results and making them more realistic. This framework implements the standard IEEE 802.11p protocol stack for vehicle communication and an obstacle model for signal attenuation. Moreover, we set the bit rate at the MAC layer to 18 Mbit/s and the transmission power to 0.98 mW. With these parameters and a two-ray ground propagation model, it is possible to reach a communication range of 200 m. Communication beacons are sent every 1 s. For all scenarios, we simulate r replications aiming to compute the confidence interval of 95% in the results. In Table 5.3, we summarize the main parameters used in the simulations.



(a) Estimated cluster coefficient (b) Node degree evolution



(c) Topological overlap

Figure 5.4: Cologne metrics evolution.

5.5.3 Metrics evaluated

Below, we present the metrics used to evaluate the performance of our solutions. The focus is to verify the coverage of the solution, the overhead induced by data messages, and the latency for different network density conditions.

- **Delivery Ratio:** the percentage of data messages the source generates to intended recipients. The closer to 100% the delivery ratio is, the greater the reliability of the data dissemination.

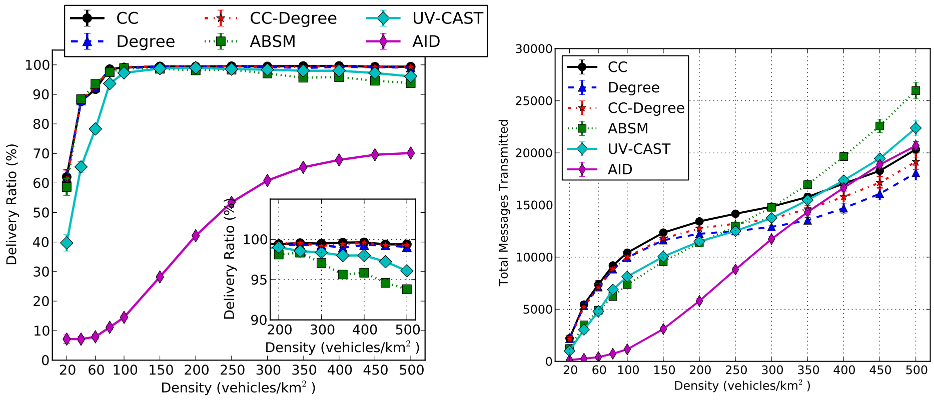
- **Total Messages Transmitted:** This metric computes the total number of data messages transmitted during the dissemination. It is an important metric to capture the number of redundant retransmissions, which may cause the broadcast storm problem.
- **Collisions:** the average number of collisions per vehicle to perform the dissemination. It is desired for a solution to induce a low number of message collisions.
- **Delay:** This is the average time a data message travels from the source vehicle to the intended recipients. Some applications in VANETs have hard delay requirements, such as alert services. For these types of services, messages must be disseminated quickly.

5.5.4 Delay-based results

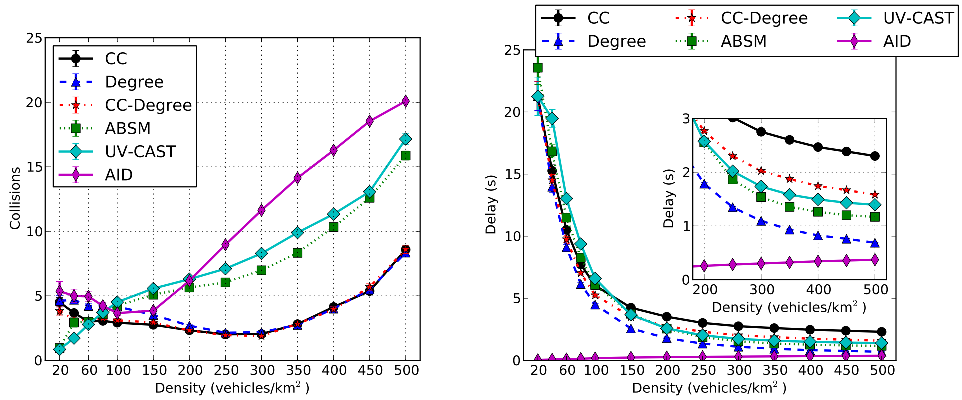
Figure 5.5 shows the results for the Manhattan grid scenario. As we can note, overall, our socially inspired solutions present a better performance. When considering the delivery ratio (Figure 5.5-(a)), for lower densities, we can observe that CC, Degree, CC-Degree, and ABSM deliver data messages to the same amount of vehicles. As the density increases, so does the delivery results for all solutions. However, for very high densities, the performance of ABSM and UV-CAST starts to deteriorate, while our proposals guarantee a 100% delivery ratio. This result shows that social metrics lead to the same delivery capability.

Figure 5.5-(b) shows the number of data messages transmitted. For lower densities, our proposals transmit more data messages when compared to ABSM and UV-CAST. As shown in the previous result, given that CC, Degree, CC-Degree, and ABSM have the same delivery results for much lower densities, we can conclude that our proposals cannot avoid redundant retransmissions when the network is sparse. Notice that the broadcast storm problem is not much of an issue in sparse networks. Our solutions incur the lowest number of data messages transmitted as the density increases. Among the three, the Degree presents the best results, while the CC the worse. Recall from the results shown in Figure 5.3 that, at higher densities, the variability for the Degree is higher when compared to the one presented by the clustering coefficient. As already stated, the greater the variability, the greater the range of possible waiting delays, which leads to a better broadcast suppression approach. In a similar result, Figure 5.5-(c) shows the number of collisions for all solutions. Essentially, the behavior is almost the same for the number of messages transmitted. Our approaches perform better at higher densities. It is worth noticing that, among our solutions, the Degree leads to the highest collisions at lower densities, while the CC leads to the lowest. This fact can also be explained by the variability results shown in Figure 5.3.

Figure 5.5-(d) shows the delay for all solutions. As expected, for lower densities, the delay for all solutions is very high due to the store-carry-forward performed by all solutions, i.e., vehicles need to store and carry messages around to deliver them. As the density increases, the delay for all solutions decreases. In particular, Degree has the lowest delay, while CC has the highest. According to the results shown in Figure 5.3, the clustering coefficient is also high for higher densities. Therefore, the waiting delays chosen by vehicle will also be high, thus explaining the higher average delay. In the case of the Degree, the node degree is also high for higher densities. However, contrary to the clustering coefficient, nodes with a high degree have a lower waiting delay, which explains the average delay in delivering data messages to intended recipients.



(a) Delivery Ratio (b) Messages Transmitted



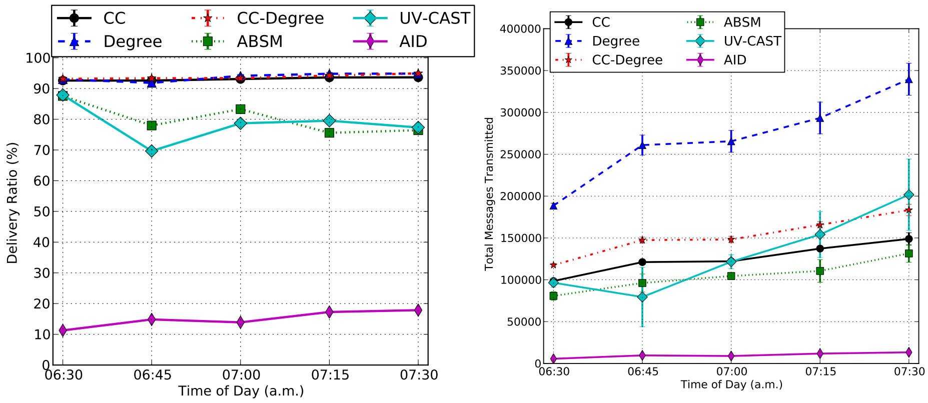
(c) Collisions (d) Delay

Figure 5.5: Simulation results for the Manhattan street scenarios.

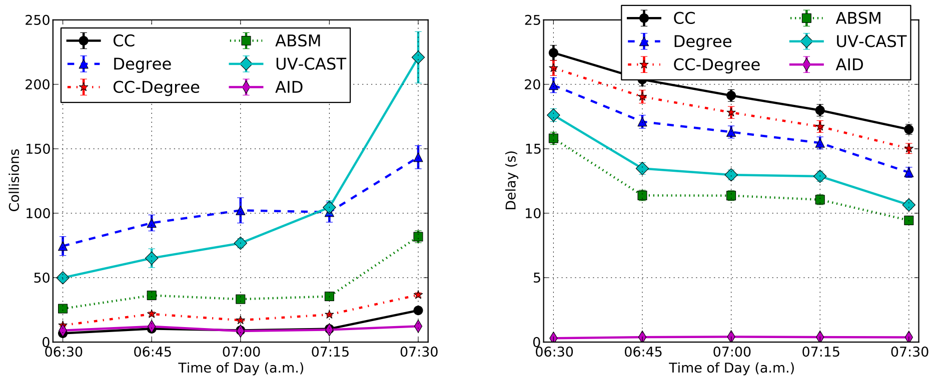
The performance results for all solutions under the Cologne scenario are shown in Figure 5.6. As in the Manhattan grid scenario, our proposed solutions also have the best delivery results (see Figure 5.6-(a)). CC, Degree, and CC-Degree can deliver about 15% more messages to intended recipients when compared to ABSM and UV-CAST. This result shows that our proposals are more reliable when compared to state-of-the-art solutions.

Figure 5.6-(b) shows the total number of data messages transmitted. CC and CC-Degree transmit the same amount as ABSM and UV-CAST, while Degree has a much higher

overhead. Recall from Table 5.2 that the densities considered in the Cologne scenario are not very high. Moreover, as shown, Degree induces a higher overhead under lower densities. Therefore, such a result was expected. The same behavior can be observed in the result for the number of collisions (see Figure 5.6-(c)). Degree induces almost the same collisions as UV-CAST, while CC and CC-Degree generate the lowest number. As expected, CC behaves better at lower densities, which explains the better performance in the Cologne scenario. Figure 5.6-(d) shows the delay result for the Cologne scenario. As can be observed, our proposed solutions have the highest delays. Such a result is intimately related to the delivery performance of our solutions when compared to the related solutions. That is due to a higher delivery ratio (about 15%) and the sparse Cologne scenario. Vehicles need to store and carry the messages for a longer time, thus explaining the higher delay.



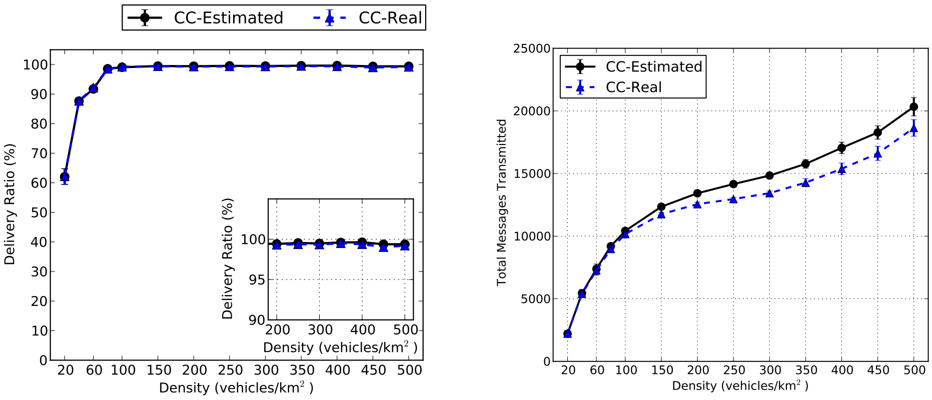
(a) Delivery Ratio (b) Messages Transmitted



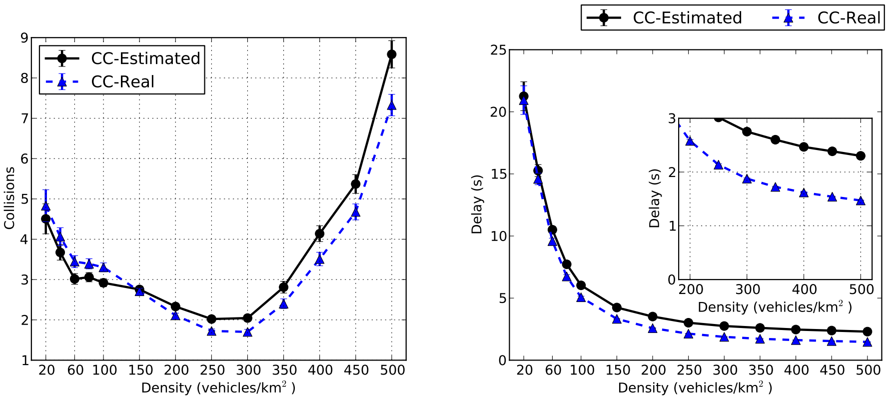
(c) Collisions (d) Delay

Figure 5.6: Simulation results for the Cologne scenario.

Finally, aiming to analyze the difference between the estimated and real cluster coefficients, we present the results for these metrics in Figure 5.7 under the Manhattan grid scenario. Recall that the estimated clustering coefficient is computed by considering the distance between vehicles and the estimated communication range. Therefore, signal attenuation caused by buildings has a direct impact on it. Conversely, the real clustering coefficient is calculated using the two-hop neighborhood knowledge of vehicles. As can be observed, overall, using the real clustering coefficient results in a better performance. However, the difference in the results of the estimated clustering coefficient is not significant, especially when we consider the extra cost to compute the real clustering coefficient.



(a) Delivery Ratio (b) Messages Transmitted



(c) Collisions (d) Delay

Figure 5.7: Comparison for performance evaluation between cluster coefficient estimated and real for the Manhattan scenario.

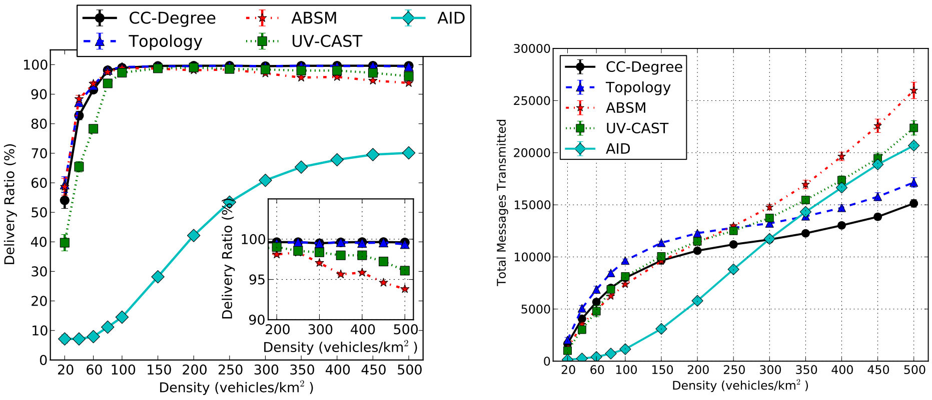
5.5.5 Probabilistic-based results

Figure 5.8 presents the results for the Manhattan scenario. In Figure 5.8-(a), we can see the evolution of the delivery ratio when the density varies. It is possible to note that the CC-Degree and Topology solutions present a better performance, with values to the delivery ratio close to 100 %. Compared with the other solutions, our solutions increase the delivery ratio in 5 %. This happens due to the function to define the probability of rebroadcasting the data message, which reduces the redundant transmissions. However, we can note the higher difference in the delivery ratio to the AID protocol, which defines its rebroadcast probability without considering the story-carry-forward mechanism. Figure 5.8-(b) presents the results of the number of messages transmitted. We note that in low-density regions, the CC-Degree and Topology solutions present a similar performance compared to the others. However, the CC-Degree and Topology present less overhead in higher densities than the other solutions, about 25 % less. It is important to remark that the broadcast suppression mechanism significantly reduces redundant transmissions.

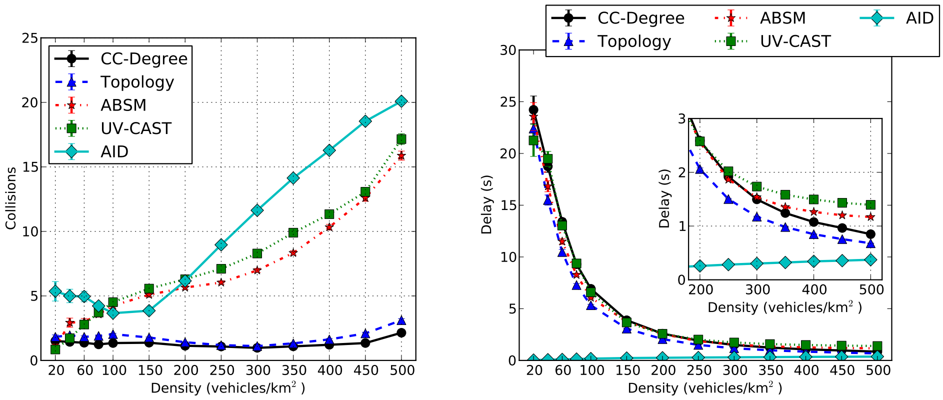
Looking at the collisions, Figure 5.8-(c), we can note that the CC-Degree and Topology present fewer collisions than the other solutions. Analyzing the density evolution, the CC-Degree and Topology present a constant behavior in the curves, decreasing the total number of collisions in 90 %. This occurs because this scenario has fixed vehicle density in the whole area. It does not present network partitions, which favors the execution of the broadcast suppression algorithm, reducing the number of redundant transmissions. Regarding Figure 5.8-(d), we can observe the evolution of the delay during the dissemination. As we can see, when we compare the CC-Degree and Topology solutions with the delay-based solutions (ABSM e UV-CAST), the performance of our solutions is similar, presenting a reduction of 1 s in scenarios with higher density. Because our solutions are probabilistic-based, the vehicles do not add delay in their transmissions, contributing to this reduction. However, the AID rebroadcasts the data message directly, reducing the delay but increasing collisions. Also, this behavior leads us to reach a low delivery ratio.

When we analyze the performance of the solutions in a sparse scenario (Figure 5.9, we note that our solutions (CC-Degree and Topology) guarantee a good delivery ratio, compared with the other solutions (Figure 5.9-(a)). The AID protocol presents the worst performance, and the delay-based solutions present a delivery ratio of 80 %. However, the CC-Degree and Topology keep the delivery ratio close to 100 %. Due to its sparse scenario, the store-carry-forward mechanism is necessary to guarantee a good delivery ratio. Regarding Figure 5.9-(b), it exhibits the results of the number of messages transmitted. As we can see, the proposed solutions present a great value compared to the others. This is an expected result when we look at the delivery ratio. By being a sparse scenario, with many partitions and low-density traffic, the solution needs to perform more transmissions to guarantee the coverage of the real ROI.

Observing the number of collisions during the evaluated period (Figure 5.9-(c)), we verify that the CC-Degree and Topology solutions present values close to ABSM and UV-Cast solutions. Also, the AID protocol presents a smaller value to collisions due to the smaller number of transmissions. In this solution, few vehicles reach the probability of rebroadcasting the data message. In Figure 5.9-(d), we note the results of the delay in the dissemination. CC-Degree and Topology present a delay slightly larger than the others. Intending to guarantee delivery in a sparse scenario, the tendency is that the delivery occurs with a more significant delay. Once again, the AID solution presents a low delay due to the worst performance on the



(a) Delivery Ratio (b) Messages Transmitted



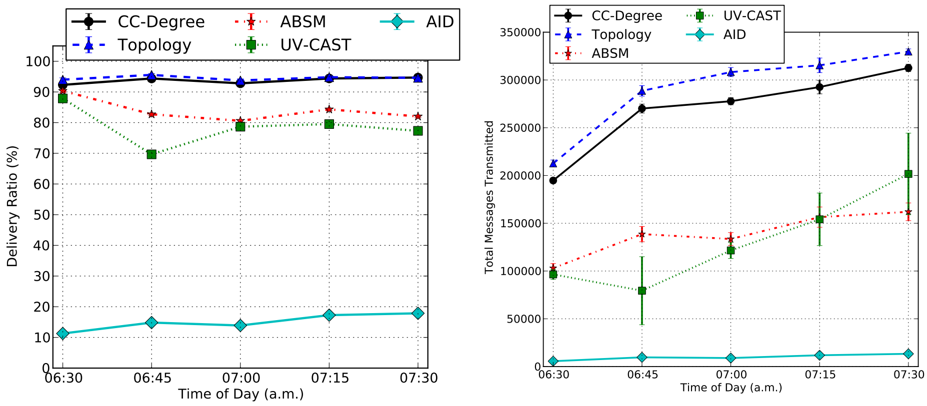
(c) Collisions (d) Delay

Figure 5.8: Simulation results for the Manhattan street scenarios.

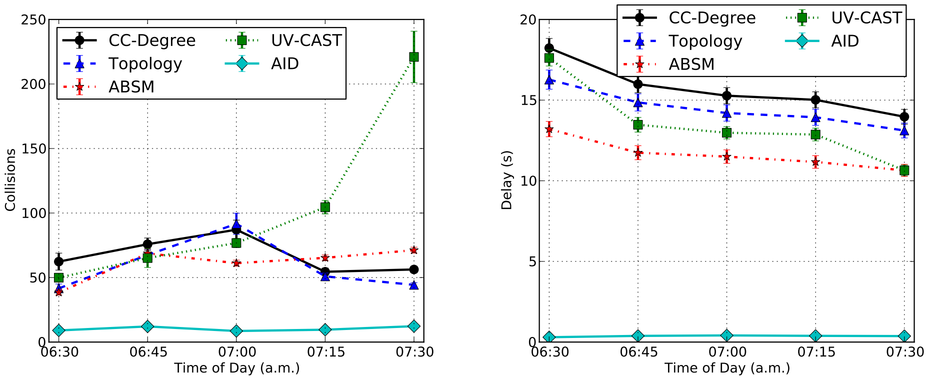
delivery.

5.6 Chapter remarks

This chapter presented two new solutions for data dissemination in vehicular ad hoc networks that consider the network's social aspects and traffic evolution. Aiming to solve the broadcast storm and the intermittently connected network problems, we proposed delay-based and probabilistic-based solutions to disseminate data. The delay-based solutions use the information about the number of neighbors (node degree) and how these neighbors are connected (clustering coefficient) as a criterion to define when and which vehicles rebroadcast data messages during the dissemination process. The probabilistic-based solutions, in addition to using the same metrics as the delay-based approaches, also use the information of similarity of contacts, i.e., the ratio of neighbors shared by two nodes (topological overlap),



(a) Delivery Ratio (b) Messages Transmitted



(c) Collisions (d) Delay

Figure 5.9: Simulation results for the Cologne scenario.

as a criterion to define the probability for each vehicle to rebroadcast the data messages.

We evaluated the performance of our approach in density and sparse scenarios. Both solutions presented substantial performance gains in high-density scenarios, especially regarding delivery capability, delay, and overhead. Our solutions presented an expressive reduction in the last two metrics. However, in sparse scenarios, our solutions guarantee good coverage. Our solution transmitted more messages in a scenario with partitions and density variations. This led to a small increase in the delay and the number of messages transmitted. Besides, this behavior is the trade-off to guarantee a good performance in sparse scenarios.

In future work, we intend to improve our solutions using more metrics that can capture more social proprieties of the network, aiming to improve the selection criteria. Also, we want to refine our performance evaluation by characterizing the factors that may impact the dissemination process, such as delay, bandwidth, and queue length.

CHAPTER

6

Final Remarks

> In the End, we will remember not the words of our enemies, but the silence of our friends.
>
> Martin Luther King

This chapter presents the final thoughts about this thesis. In Section 6.1, we reinforce the achieved contributions while we provide our view about future research directions that can follow from this work. Section 6.2 shows the list of publications we achieved during this work.

6.1 Conclusion and Outlook

The main objective of this thesis is to study vehicular networks and the interactions among vehicles, to understand these interactions better, and to take advantage of them to promote services, protocols and improve the connectivity in the network. We were also interested in how interactions happen in the networks and how people's lifestyles impact interactions. We started our work by presenting an overview of the vehicular networks. We discussed each layer in the network, presenting the main characteristics of vehicular networks, architecture details, standards, and protocols found in the literature. We also discussed the type of applications, showing the peculiarities of each type and some examples found in the literature.

With a focus on studying the interactions, we presented a description of the main entities in the network, where we enumerated the features and behaviors of each one. We also defined the interactions among these entities, discussing the factors that can impact interactions and applications created by these interactions. Considering the interactions among the vehicles, we presented a characterization of vehicular traces that describes the mobility of vehicles along the city. We showed that it is possible to classify the interactions among the vehicles according to the people's behavior and their routines.

Considering the data dissemination task, in this work, we developed a new solution to perform data dissemination on vehicular networks aware of the interactions. We explored the vehicles-to-vehicles interactions aiming to rebroadcast a data packet and deliver it to a group of vehicles inside a region of interest. Thus, at the moment, to define the forwarder vehicle to the data packet, we use metrics that quantify the influence of these vehicles on the network. With our solution, we could verify new possibilities to tackle the common problems in data dissemination when we know interactions.

This work presents several possibilities for future research. For instance, it is possible to design new services and protocols for vehicular networks aware of the interactions among the vehicles, mobile devices, and smart infrastructure. These entities open new perspectives to VANETs, providing new data sources to explore through interactions. On the other hand, considering the behaviors of the vehicles and their interactions, we can also explore the characterization to study the interactions among other entities and quantify the influence of other factors on interactions. Also, from the perspective of data dissemination, this work can be extended to explore the presence of common interests and communities in the network to improve the data dissemination task.

6.2 Publications

In the following sections, we present a list of publications produced in the Ph.D. The list is divided into periodicals, conference papers, book chapters, and short courses. Those identified with a (⋆) are directly related to this work.

6.2.1 Periodicals

- ⋆ Cunha, Felipe D.; Guilherme; Guidoni, Daniel; Viana, Aline C.; Mini, Raquel A. F.; Loureiro, Antonio A. F., **Interactions in Vehicular Networks: Fundamentals and Applications**, *Submitted to Computers Magazine*

- ⋆ Cunha, Felipe D.; Villas, Leandro A.; Boukerche, Azzedine; Maia, Guilherme; Viana, Aline C.; Loureiro, Antonio A. F., **Data Communication in VANETs: A Survey, Challenges and Applications**. *Ad Hoc Networks* - 2016

- ⋆ Mota, Vinicius M.; Cunha, Felipe D.; Macedo, Daniel F.; Nogueira, Jose Marcos S.; Loureiro, Antonio A F., **Protocols, Mobility models and Tools in Opportunistic Networks: A Survey**. *Computer Communications* - 2014

6.2.2 Conferences and Workshops

- ⋆ Cunha, Felipe D.; Maia, Guilherme; Villas, Leandro; Viana, Aline C.; Mini, Raquel A. F.; Loureiro, Antonio A. F., **To Forward or Not to Forward the Message? A Probabilistic Data Dissemination Solution for Vehicular Ad Hoc Networks**, *41st IEEE Conference on Local Computer Networks - IEEE (LCN 2016)*, Dubai, UAE, 2016. (waiting for response)

  Brennand, Celso; Felipe D.; Maia, Guilherme; Cerqueira, Eduardo; Loureiro, Antonio A. F.; Villas, Leandro, **FOX: A Traffic Management System of Computer-Based Vehicles FOG**, *21th IEEE Symposium on Computers and Communications - IEEE (ISCC 2016)*, Messina, Italy, 2016.

- ⋆ Alvarenga, Davidysson A.; Cunha, Felipe D.; Viana, Aline C.; Mini, Raquel A. F.; Loureiro, Antonio A.F., **Classificando Comportamentos Sociais em Redes Veiculares**, *Simpósio Brasileiro de Redes de Computadores*, Bahia, Brasil, 2016.

- ⋆ Cunnha, Felipe D.; Silva, Fabrício A.; Celes, Clayson S. F. S.; Menezes, João G. M. ; Ruiz, Linnyer B.; Andrade, Rossana M. C.; Mini, Raquel. A.F.; Boukerche, Azzedine; Loureiro, Antonio A. F., **Communication Analysis of Real Vehicular Calibrated Traces**. *In: IEEE International Conference on Communications (ICC)*, 2016, Kuala Lumpur.

- ⋆ Ferreira, Bruno; Cunha, Felipe D.; Mini, Raquel. A.F.; Loureiro, Antonio A. F.; Braz, Fernando A. F.; Campos, Sérgio V. A., **Intelligent Service to Perform Overtaking in Vehicular Networks**. *In: IEEE Symposium on Computers and Communication (ISCC), 2015, Larnaca.*

- ⋆ Cunha, Felipe D.; Alvarenga, Davidysson A.; Viana, Aline C.; Mini, Raquel A. F.; Loureiro, Antonio A. F., **Understanding Interactions in Vehicular Networks Through Taxi Mobility**. *In: 12th ACM International Symposium on Performance Evaluation of Wireless Ad Hoc, Sensor, and Ubiquitous Networks (PE-WASUN)*, 2015, Cancun, Mexico.

- ⋆ Cunha, Felipe D.; Maia, Guilherme; Viana, Aline C.; Mini, Raquel A. F.; Villas, Leandro; Loureiro, Antonio A. F., **Socially Inspired Data Dissemination for Vehicular Ad Hoc Networks**, *17th ACM International Conference on Modeling, Analysis and Simulation of Wireless and Mobile Systems (MSWiM'14)*

- ⋆ Cunha, Felipe D.; Viana, Aline C.; Mini, Raquel A. F.; Loureiro, Antonio A. F., **Is it Possible to Find Social Properties in Vehicular Networks?**, *19th IEEE Symposium on Computers and Communications - IEEE (ISCC 2014)*

- ⋆ Cunha, Felipe D.; Viana, Aline C.; Mini, Rodrigues, Thiago; Raquel A. F.; Loureiro, Antonio A. F., **Extração de Propriedades Sociais em Redes Veiculares**, *Workshop de Redes P2P, Dinâmicas, Sociais e Orientadas a Conteúdo (SBRC 2014 - WP2P+)*

- ⋆ Cunha, Felipe D.; Viana, Aline C.; Mini, Raquel A. F.; Loureiro, Antonio A. F., **Are Vehicular Networks Small World?**,*IEEE INFOCOM - Student Activities (Posters)*, Toronto - Canadá.

- ⋆ Cunha, Felipe D.; Viana, Aline C.; Mini, Raquel A. F.; Loureiro, Antonio A. F., **How effective is to look at a Vehicular Network under a Social Perception?**. *In: Internet of Things Communications and Technologies (IoT 2013) in conjunction with IEEE WImob 2013* Lyon - France.

  Boukerche, Azzedine; Villas, Leandro A.; Guidoni, Daniel L.; Maia, Guilherme; Cunha, Felipe D.; Ueyama, Jo; Loureiro, Antonio A.F. . **A new solution for the time-space localization problem in wireless sensor network using UAV**. *In: Third ACM international symposium on Design and analysis of intelligent vehicular networks and applications - DIVANet '13.* 213, Barcelona - Espanha.

  Cunha, Felipe D.; Cunha, Ítalo F. S.; Wong, H. C.; Loureiro, Antonio A. F.; Oliveira, Leonardo B., **ID-MAC: An Identity-Based MAC Protocol for Wireless Sensor Networks**.*In: IEEE Symposium on Computers and Communications*, 2013, Split - Croatia.

  Oliveira, Leonardo B.; Cunha, Ítalo F. S.; Cunha, F. D.; Loureiro, Antonio A. F., **Uma Nova Abordagem para Acesso ao Meio em Redes de Sensores Sem Fio**. *In: Simpósio Brasileiro de Redes de Computadores e Sistemas Distribuídos*, 2013, Brasília - Brasil.

  Melo, Pedro O. S. V.; Cunha, Felipe D.; Loureiro, Antonio A. F., **A Distributed Protocol for Cooperation Among Different Wireless Sensor Networks**. *In: International Conference on Communications (ICC'13)*, 2013, Budapest - Hungary.

  Cunha, Felipe D.; Mini, Raquel A. F.; Loureiro, Antonio A. F., **Sensor-MAC with Dynamic Duty Cycle in Wireless Sensor Networks**. *In: IEEE Global Telecommunications Conference, (Globecom'12)*, 2012. Anaheim - USA.

6.2.3 Book Chapters

- ⋆ Cunha, Felipe D.; Maia, Guilherme; Viana, Aline C.; Adjih, Cedric; Mini, Raquel A. F.; Loureiro, Antonio A. F., **Understanding Interactions in Vehicular Networks**, in Book Graph Theoretic Approaches for Analyzing Large-Scale Social Networks - IGI Global - 2017. *Book chapter proposal submitted*

- ⋆ Cunha, Felipe D.; Maia, Guilherme; Villas, Leandro; Viana, Aline C. ; Mini, Raquel A. F.; Loureiro, Antonio A. F., **Socially Inspired Data Dissemination for Vehicular Ad Hoc Networks**, *Book chapter accepted - CRC PRESS* - 2016

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6.2.4 Short Course

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APPENDIX

A

Delay Evaluation in Data Dissemination

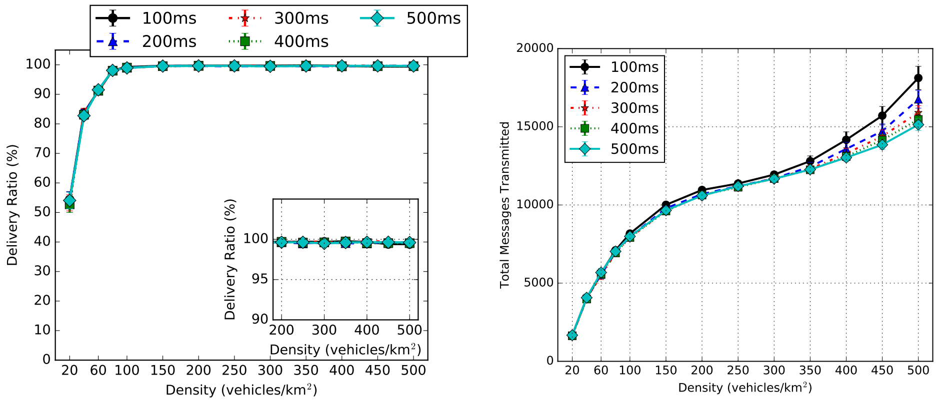
A.1 Introduction

In Vehicular Ad hoc Networks (VANETs), data dissemination can experience delays due to various factors. Here are some common reasons for data dissemination delays in VANETs:

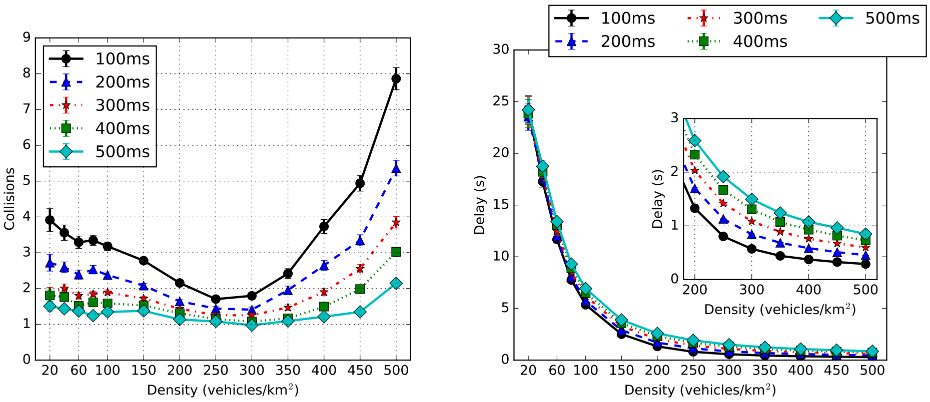
- **Network Congestion:** When many vehicles simultaneously try to access and transmit data in a VANET, it can lead to network congestion.
- **Communication Range:** Vehicles in a VANET can only communicate directly with neighboring vehicles within their communication range, making reaching nearby vehicles challenging.
- **High Mobility:** Vehicles in VANETs are constantly moving, and their connectivity can be transient due to their changing positions, which generates frequent link disruptions and reconfigurations.
- **Wireless Interference:** VANETs operate in a shared wireless medium, and interference from other devices or networks can affect data dissemination.
- **Routing Protocol Overhead:** In VANETs, the routing protocols use mechanisms of control messages, route establishment, and maintenance processes, which introduce additional overhead and can contribute to data dissemination delays.

Concerning the proposed solutions, in the following two sections, we explore our solutions exploring the vehicle density and the maximum forward delay. In Section A.2, we present the results for the performance evaluation for the Joint Solution, and in Section A.3, the results for the Topology Solution.

A.2 Joint Solution



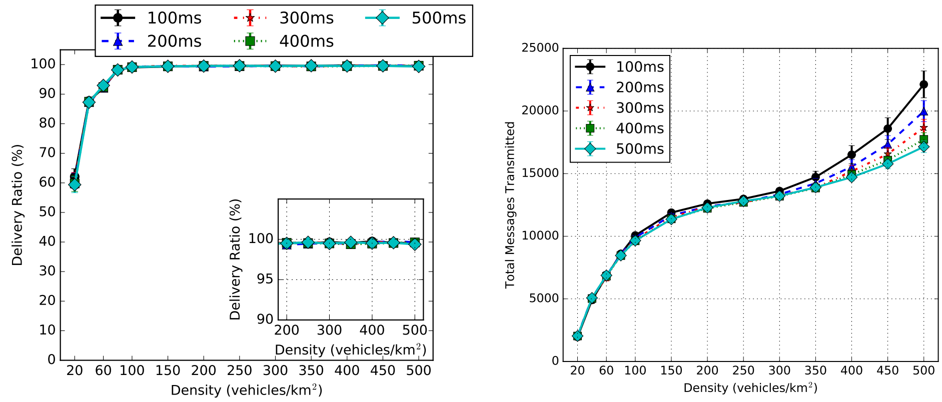
(a) Delivery Ratio (b) Messages Transmitted



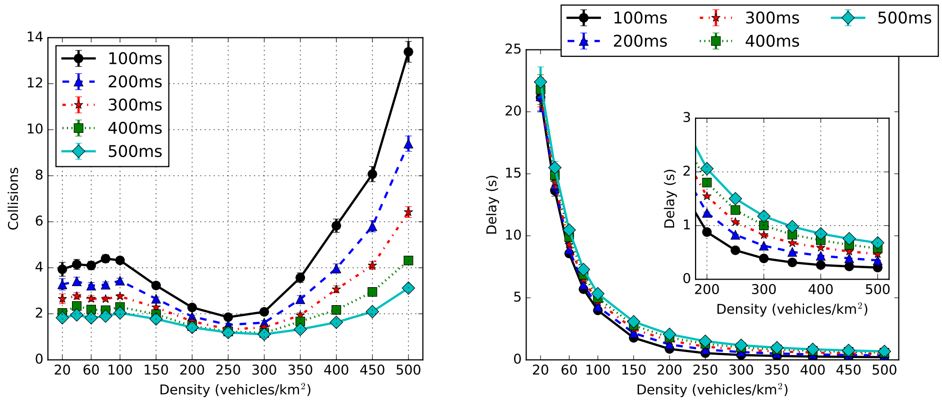
(c) Collisions (d) Delay

Figure A.1: Simulation results for the Cologne scenario.

A.3 Topology Solution



(a) Delivery Ratio (b) Messages Transmitted



(c) Collisions (d) Delay

Figure A.2: Simulation results for the Cologne scenario.

APPENDIX

B

Fatorial Design Factors Data Dissemination

Factorial Design is an experimental statistical technique that allows researchers to study the effects of multiple independent variables on a dependent variable. In a Factorial Design, the independent variables are manipulated at different levels aiming to examine how these variables interact and affect the outcome.

In this appendix, it will be described, step by step, a Factorial Design that evaluates the interactions between the two variables α and β [Jain, 1991]. We used these variables to define the probability of forwarding a packet in the Jointly Solution presented in Chapter 5. Section B.1 describes the main terms used in analyzing a Factorial Design Factor project, and Section B.2 presents the results of our Factorial Design $2^k r$.

B.1 Factorial Design

Factorial designs are widely used in various fields, including psychology, social sciences, engineering, and manufacturing. They allow researchers to examine multiple factors simultaneously and understand how they interact to influence the dependent variable.

The advantages of factorial design include:

- Efficiency: By examining multiple factors simultaneously, factorial designs require fewer experimental runs than conducting separate experiments for each factor.
- Interactions: Factorial designs allow researchers to detect interaction effects between independent variables, providing insights into how factors may influence each other.
- Generalizability: Factorial designs help researchers understand the general effects of factors on the dependent variable rather than focusing on individual effects in isolation.

However, factorial designs also have some limitations, such as increased complexity in experimental design, data analysis, and interpretation. Additionally, the number of experimental conditions can quickly grow as more factors and levels are added, which may require a larger sample size.

Many are the names and terms used to execute a Factorial Design, and following, we define these terms frequently used in a Factorial Design to execute and analyze the results.

- **Response Variable:** The result of an experiment is called the response variable. Usually, the response variable is the measure of system performance.
- **Factors:** Each variable that affects the response variable and has multiple alternatives is called a factor. They may also be known as predictor variables or parameters.
- **Levels:** The value each factor can assume is called it's level. In other words, a level constitutes an alternative value for a factor.
- **Primary Factors:** are those factors whose effects need to be quantified, and through experimental design, these effects can be quantified.
- **Secondary Factors:** are factors that influence performance, but there is no interest in assessing their impact.
- **Replication:** Repeating some or all experiments is called replication. For example, if all experiments in the case study were repeated 20 times, then the case study is said to have 20 replications.
- **Design:** An experimental design specifies the number of experiments, combinations for factor levels, and the number of replications for each experiment.
- **Interaction:** Interaction between two factors, A and B, exists when one factor depends on the level of the other.

B.2 Factorial Design Results

In this section, we describe the methodology used to evaluate the impact of the clustering coefficient and node degree metrics on the performance of the joint solution. The focus of the analysis is to demonstrate the influence of each metric on the proposed solutions. Also, we intend to measure how the interactions among the vehicles can impact the data dissemination task. The first metric, *clustering coefficient*, will portray how close the vehicles are connected, i.e., the ratio of connections among the vehicles and their neighbors. Thus, with a higher cluster coefficient, the probability of having more collisions in the data dissemination will be higher. On the other hand, lower values for the clustering coefficient can indicate traffic sparsely with more probability of network fragmentation.

The second metric, *node degree*, determines the number of connections a vehicle have, i.e., in data dissemination, a vehicle that portrays a high node degree will have a significant probability of reaching more vehicle with its transmission. With this metric, we intend to give more importance to the vehicles with higher node degrees, aiming to reduce the number of transmissions and improve the data dissemination coverage.

We performed this evaluation through one Factorial Design $2^k r$, described in Jain [1991], where k means the number of factors chosen to evaluate, r denotes the number of replications, and 2 the number of levels that each factor can assume. The purpose of this analysis is to identify, among the metrics evaluated, which parameter has a significant impact on the data dissemination process. Aiming to diminish the error in the evaluation, we simulate each configuration r times. Thus, the results will be more statistically notable. The mathematical model used to calculate the $delay$ and $collision$ is, then:

$$delay = q_0^{delay} + q_\alpha^{delay} X_\alpha + q_\beta^{delay} X_\beta + q_{\alpha\beta}^{delay} X_\alpha X_\beta + e^{delay} \tag{B.1}$$

$$collision = q_0^{collision} + q_\alpha^{collision} X_\alpha + q_\beta^{collision} X_\beta + q_{\alpha\beta}^{collision} X_\alpha X_\beta + e^{collision} \tag{B.2}$$

As we can see in Equation where q_0^{delay} and $q_0^{collision}$ represent the average values for the $delay$ and $collision$. The coefficients q_α^{delay} and $q_\alpha^{collision}$ are, respectively, the ones that represent the effect of the *node degree* on the average of q_0^{delay} and $q_0^{collision}$. The coefficients q_β^{delay} and $q_\beta^{collision}$, in turn, are the ones that account for the effect of the *clustering coefficient* on q_0^{delay} and $q_0^{collision}$. The interaction between the two metrics is captured by the coefficients $q_{\alpha\beta}^{delay}$ and $q_{\alpha\beta}^{collision}$, respectively. The constants e^{delay} and $e^{collision}$ are the experimental errors of the models. X_α and X_β are the categorical variables that assume values -1 and 1 to indicate the level of the factors α and β, described in the Table B.1.

X_α, X_β	α	β
-1	0.2	0.2
1	0.5	0.5

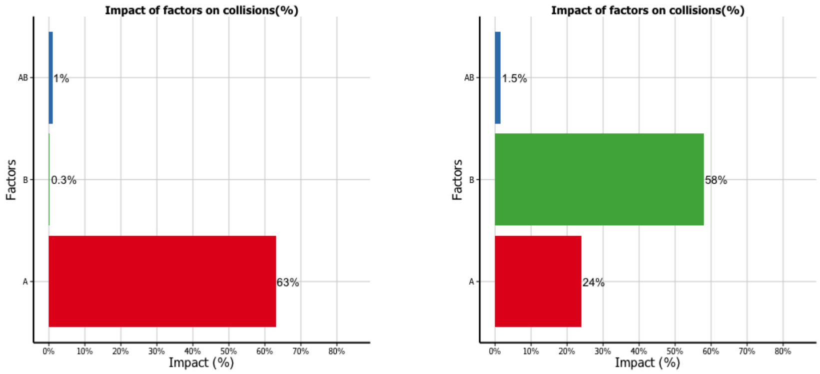
Table B.1: Solution parameters configuration for the two factors: X_α, X_β

In this evaluation, we set up the data dissemination process in the Manhattan scenario, with a vehicle density of 250 vehicles/km^2. In this scenario, we have one vehicle source, which will start the dissemination, and the other vehicles cooperating to cover the whole area of interest. According to Table 5.3, we define all the default parameters.

X_α	X_β	$X_\alpha X_\beta$	**delay**	**collision**
-1	-1	1	70.63	15.7
-1	1	-1	61.09	20.5
1	-1	-1	68.98	22.65
1	1	1	61.70	25.55
-4.2	-0.2	0.56	q^{delay}	–
63%	0.3%	1%	$\%q^{delay}$	–
1.9	3.0	-0.45	–	$q^{collision}$
24%	58%	1.5%	–	$\%q^{collision}$

Table B.2: Results of Factorial Design 2^2r.

Table B.2 shows the simulation results for each configuration. Each line presents the average of delay and collision according to the configuration defined by the level of α e β. The final lines present the effect of each factor over the $delay$ and $collision$, while the lines $\%q^{delay}$ and $\%q^{collision}$ represent, respectively, the impacts of each factor on the values of $delay$ and $collision$. Thus, the coefficient q_α^{delay} is -4.2, indicating that when the value of α is -1 (0.2), $delay$ is added by 4.2 s., and when α is 1 (0.5), the $delay$ is subtracted by 4.2 s., which represents an effect of 63% of the metric *node degree* on the $delay$ value. For the coefficient q_β^{delay}, we can also observe that its variation does not produce a high impact on the *delay*, only 0.3%. As expected, the metric *clustering coefficient* does not have a significant impact on the *delay*. It just portrays the proximity of the vehicles.



(a) delay metric.

(b) collision metric.

Figure B.1: Factor impact on delay and collisions.

As for the *collision*, we can observe that $q_\beta^{collision}$ has a great impact on the number of the collision, around 58% of influence. This influence occurs because this factor portrays how close the vehicles are, i.e., the network's density. The more dense the network is, the higher the probability of collisions in a transmission. Moreover, in contrast with the $q_\beta^{collision}$, the $q_\alpha^{collision}$ also has an impact on the number of collisions, about 24%. This behavior can be explained by the fact that the *node degree* reflects the number of connections the node has, and the higher this value, the greater the likelihood of a collision.

An interesting conclusion from the results of this Factorial Design is that each factor has a different impact on the different metrics in the performance of the data dissemination solution. In this evaluation, *node degree* impacts more on *delay*, and *clustering coefficient* on the *collision*, according to the feature and property that each metric portrays.