Master of Science Thesis

Evaluation of and Improvement to Decentralized Congestion Control via Transmit Power Control with Information Exchange in ETSI GeoNetworking

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Evaluation of and Improvement to Decentralized Congestion Control via Transmit Power Control with Information Exchange in ETSI GeoNetworking

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I dedicate my efforts during my studies at TU Delft to the most important persons in my life.

To my dear parents for their efforts, dedication, sacrifice and love to provide me with the mindset and tools to face life. For my sisters for their love, wishes and trust.

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Alejandro Augusto Jiménez Luna
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Abstract

Intelligent Transport Systems (ITS) involves the technology currently addressed for future car-to-car and car-to-infrastructure communication. ITS aim to increase safety, optimize traffic flows, decrease polluting emissions and facilitate e-commerce. The European Commission (EC) has instructed European Telecommunications Standards Institute (ETSI) and other parties to take the role to develop and standardize the protocols and algorithms for car-to-car communication. As for any wireless (or wired) network, congestion of the communication channels represents one of the main challenges for ITS technology, given the fact that such vehicular networks involve rapidly changing topologies. To mitigate this, so-called Decentralized Congestion Control (DCC), developed under ETSI research uses Transmit Rate Control (TRC) and Transmit Power Control (TPC).

This thesis work is focused on the development and assessment of new DCC solutions in the TPC family. We propose the use of classical control loop theory concepts and information sharing at the OSI (Open Systems Interconnection) access layer. We present two algorithms a) TPC with simple proportional-integral (PI) control loop (TPC PI), which aims to alleviate the effects of high channel load on network performance based on TPC and b) TPC with PI control loop and exchange of channel load share information (TPC CLS), which aims to alleviate the effects of high channel load on network performance based on TPC and information about neighbors. In order to implement and assess our proposed solutions we use ns-3 network simulator and SUMO vehicular traffic simulator. Our results are mainly presented in terms mainly of channel load (CL) and Packet Delivery Ratio (PDR).

Our results show that both solutions are able to control channel load under static and mobile vehicles scenarios while keeping channel load in a near-steady state. This means that under both approaches the oscillating pattern seen with ETSI DCC is eliminated. We observe that for scenarios without randomized mobility the PDR is significantly improved in comparison to IEEE 802.11p and ETSI DCC for transmission-reception distances up to 100 m. In particular, TPC CLS shows an improvement in PDR values in comparison with TPC PI. However, for scenarios with mobility and random inter-vehicle distances the benefits of both approaches were diminished and at a certain point the attained performance is similar to that of simple IEEE 802.11p and ETSI DCC.

Even though our TPC CLS approach proved to be efficient in several cases and scenarios it still takes local information on its channel load share based on the number of detected neighbors. In this thesis work we decided to choose information of the vehicles’ neighborhood to improve the performance of the network. Despite the results and the improvement of ETSI DCC performance results, we think that the share of information among vehicles in a vehicular network is beneficial but in our case is shown to be not enough to assure high performance for the more realistic scenarios. However, we also think that information share leads to a tradeoff between how much information is useful to improve performance and how much overhead is added to the communication channels by sharing certain amount of information.
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LIST OF ACRONYMS

AC  Access Categories
ACK  Acknowledgment
AIFS  Arbitration Inter Frame Spacing
AIMD  Additive Increase and Multiplicative Decrease
BSS  Basic Service Sets
BTP  Basic Transport Protocol
CAM  Cooperative Awareness Message
CBR  Channel Busy Ratio
CBT  Channel Busy Time
CCA  Clear Channel Assessment
CCH  Control Channel
CEN  Comité Européen de Normalisation
CENELEC  Comité Européen de Normalisation Électrotechnique
C-ITS  Cooperative Intelligent Transport Systems
CL  Channel Load
CLR  Channel Load Reference
CLS  Channel Load Share
COMPOW  Common Power
CS  Carrier Sense
CSMA/CA  Carrier Sense Multiple Access with Collision Avoidance
CTS  Clear To Send
CW  Contention Window
D2D  Device to Device
DCC  Decentralized Congestion Control
DCF  Distributed Coordination Function
DENM  Decentralized Environmental Notification Message
D-FPAV  Distributed Fair Power Adjustment for Vehicular Environments
DGs  Directorate-Generals
DIFS  Distributed Interframe Space
DOT  Department of Transportation (U.S.)
DSC  DCC Sensitivity Control
DSRC  Dedicated Short Range Communications
ED  Energy Detection
EDCA  Enhanced Distributed Channel Access
EN  European Standards
ETSI  European Telecommunications Standards Institute
ETSI  TC ITS European Telecommunications Standards Institute Technical Committee for ITS
FCC  Federal Communications Commission
GNSS  Global Navigation Satellite System
GPL  General Public License
GPS  Global Positioning Systems
HTG  Harmonization Task Groups
I2I  Infrastructure-To-Infrastructure
I2V  Infrastructure-To-Vehicle
IBSS  Independent BSS
IDM  Intelligent Driver Model
INTERN  Integration of Congestion and Awareness Control
IP  Internet Protocol
ITS  Intelligent Transportation Systems
LIMERIC  Linear Message Rate Integrated Control
LLC  Logical Link Control
LOC  LLocation Table
LOS  Line Of Sight
LTE  Long Term Evolution
MAC  Medium Access Control
MANET  Mobile Ad-Hoc Network
MIB  Management Information Base
MO  Multi-Channel Operation
MOVE  Mobility and Transport
MTI  Maximum Tolerable Interference
NAV  Network Allocation Vector
NDL  Network Design Limit
NLOSv  Non-Line of Sight Due To Vehicles
OCB  Outside the Context of a BSS
<table>
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<tr>
<td>OFDM</td>
<td>Orthogonal Frequency Division Multiplexing</td>
</tr>
<tr>
<td>OSI</td>
<td>Open Systems Interconnection</td>
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<td>PHY</td>
<td>Physical</td>
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<tr>
<td>PI</td>
<td>Proportional-Integral</td>
</tr>
<tr>
<td>PULSAR</td>
<td>Periodically Updated Load Sensitive Adaptive Rate Control</td>
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<tr>
<td>QoS</td>
<td>Quality of Service</td>
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<tr>
<td>RSU</td>
<td>Remote Side Unit</td>
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<tr>
<td>RTS</td>
<td>Request To Send</td>
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<tr>
<td>SAP</td>
<td>Service Access Point</td>
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<tr>
<td>SAP</td>
<td>Subnetwork Access Protocol</td>
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<tr>
<td>SCH</td>
<td>Service Channel</td>
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<tr>
<td>SIFS</td>
<td>Short Inter Frame Space</td>
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<tr>
<td>SINR</td>
<td>Signal to Interference and Noise Ratio</td>
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<td>SISO</td>
<td>Single Input Single Output</td>
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<td>STF</td>
<td>Special Task Forces</td>
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<td>SUMO</td>
<td>Simulation of Urban Mobility</td>
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<td>TAC</td>
<td>Transmit Access Control</td>
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<td>TDC</td>
<td>Transmit Data Rate Control</td>
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<td>Transmit Power Control</td>
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<td>TRC</td>
<td>Transmit Rate Control</td>
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<tr>
<td>TS</td>
<td>Technical Specification</td>
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<td>TSB</td>
<td>Topological-Scoped Broadcast</td>
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<td>TXOP</td>
<td>Transmit Opportunity</td>
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<tr>
<td>UMTS</td>
<td>Universal Mobile Telecommunications System</td>
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<td>UP</td>
<td>User Priorities</td>
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<td>V2I</td>
<td>Vehicle-To-Infrastructure</td>
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<td>V2V</td>
<td>Vehicle-To-Vehicle</td>
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<td>VANET</td>
<td>Vehicular Ad-Hoc Network</td>
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<td>WAVE</td>
<td>IEEE Wireless Access in Vehicular Environments</td>
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<tr>
<td>WI-FI</td>
<td>Wireless Fidelity</td>
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Intelligent Transportation Systems (ITS) will enhance future transportation systems by applying the advances in different technological fields [30]. More concrete, ITS aim to increase safety, optimize traffic flows, decrease polluting emissions and facilitate e-commerce. Wireless communication is a key technical component in the pursue of efficient ITS because it offers the mechanisms to achieve reliable and robust information exchange between for instance, vehicles, roadside control systems and sensors, back-office services and vulnerable road users like pedestrians. Currently, in ITS, the main focus is on realizing vehicle-to-vehicle (V2V), vehicle-to-infrastructure (V2I), infrastructure-to-vehicle (I2V), and infrastructure-to-infrastructure (I2I) communications [30].

One of the most important candidate technologies in Europe for wireless communication are ITS-G5 for the short range (up to a few hundred meters) [6] and cellular technologies like UMTS (Universal Mobile Telecommunications System) and LTE (Long Term Evolution) for the long range [43]. 5G technology has also been projected as the next generation in mobile communications in the upcoming years, providing convergence of Internet services with existing mobile networking standards. One of the components of the 5G architecture which is currently being investigated in the V2V field is D2D (Device to Device) communication. D2D a radio technology enabling devices to communicate at close distance by sharing the resources used by regular cellular equipment [46]. ITS-G5-based wireless communication is derived from regular Wireless Fidelity (Wi-Fi throughout) technologies, or more formally WLAN technologies, based upon IEEE 802.11. For safety-related ITS applications, an amendment named IEEE 802.11p was integrated into the IEEE 802.11-2012 WLAN standard [62]. In Europe, the ITS-G5 technology (a variant of IEEE 802.11p) is considered as the most important candidate for safety-related, short-range wireless communications. ITS-G5 focuses on functionalities at the physical and data link layers, similar to the layers described by the well-known Open Systems Interconnection (OSI) architecture [69]; it is the main focus of this thesis.

The deployment of a wireless-communication technology next to cellular systems is primarily because information exchange within the direct neighborhood of a vehicle is a priority for ITS. More specifically, safety-related applications (collision avoidance, platooning, merging, etc.) are thought to be improved, or even possible at all, with the exchange of actual vehicle/infrastructure information like speed, heading, position, etc. It is widely accepted that the cellular technologies deployed at the present time, do not meet the strict requirements (especially in terms of latency and broadcast support) for the most safety-critical applications, although recently, all-cellular approaches towards ITS are discussed more and more with the development of successors to LTE as mentioned above.

Safety-related information has to be sent periodically at a rate fast enough to assure its usefulness in scenarios that change rapidly by nature. Vehicular wireless communications based upon ITS-G5 (in fact, upon IEEE 802.11p), unlike typical WLAN networks, work in ad-hoc mode without centralized access point infrastructure. Therefore, the overhead related to (de)association, authentication and beacons mechanisms is avoided. Acknowledgements and retransmissions are also avoided in ITS-G5 for two reasons. First, most transmissions are of broadcast nature, for which the use of acknowledgements could easily lead to an overwhelming number of acknowledgements in reply, and moreover, a sender typically does not know the actual
set of receivers for which the transmission is destined. In other words, even with the availability of acknowledgements, the sender still does not know whether all (relevant) stations received its message. Second, the data to be exchanged often has a limited time during which it is useful or even valid. The use of retransmissions in such cases is often counter-productive because they induce an additional load on the wireless channel for data that may already be invalid.

At higher layers, the GeoNetworking protocol stack (part of the Networking and Transport layer and working up to the Application layer) will support the core communication technologies of ITS in Europe for V2V, V2I and I2V communications [6]. One of the main objectives of GeoNetworking is the reliable dissemination of data packets, e.g., safety and non-safety, to stations that are being addressed by their location instead of by their identity, the latter of which is more common, for instance, in protocols like IP. As an example, in one of the GeoNetworking transfer modes, called GeoBroadcast, a message is addressed to all stations in a target region (a geographically bounded area) [9].

An important vulnerability of ITS-G5 (and related) technologies is the severe degradation of communication performance if too many transmission attempts are made in a certain geographical region. Without taking special measures, the single 10 MHz channel allocated for ITS-G5 safety applications will suffer from high collision and high packet-loss rates in demanding, high-density vehicular scenarios. To mitigate this, so-called Decentralized Congestion Control (DCC), developed and under research by the European Telecommunications Standards Institute (ETSI), is an important functional aspect of the protocol stack) [24]. It is expected to keep the load on the underlying physical channel between reasonable operational bounds in order to maintain sufficient network performance. Several policies can be pursued for DCC like controlling the maximum number of messages transmitted by a station in a given period of time, also referred to as Transmit Rate Control (TRC), or controlling the interference range of individual transmissions through Transmit Power Control (TPC) [24].

The main policy used for DCC in Europe is the reduction of the per-station message rate (TRC) and transmission range (TPC) in case the channel load becomes too high. In reality, a specialized control loop is proposed which utilizes a machine state philosophy as we later address. A disadvantage of this approach is that in order to reduce the number of transmissions due to a channel-overload condition, a control-loop to that purpose has to cross several layers in the protocol stack, up to the application itself, because that is where typically the decision on message frequency is made. In contrast, a TPC control loop can typically be designed and realized in only the lowest layers of the OSI stack. Therefore, it can be exactly tailored to the communication technology at hand. This, we believe makes them easier to tune and maintain.

This thesis work is focused on the development and assessment of new DCC solutions in the TPC family. Existing TPC solutions have room for improvement as they still face challenges to achieve an optimized trade off when increasing the transmit power of a given station: increased throughput and quality of the communication link at the cost of increased interference levels. Our expectation is that ETSI DCC can be improved to obtain better performance results by focusing our efforts on the manipulation of the transmit power levels (and therefore transmission ranges) of neighboring stations. More specifically, we propose an approach that uses information sharing via the implementation of a control loop mechanism at the access layer. One of the objectives is to probe the benefits of including information such as the number of neighbors within the range of a given station and how this data might enhance the current control loop adopted by ETSI DCC.

1.1. Research questions
This thesis work aims to answer the following questions:

1. What is the performance, in terms mainly of packet delivery ratio, of ETSI’s current Decentralized Congestion Control mechanism (based on TPC and TRC)?

2. How can the performance be improved by newly developed TPC-based DCC solutions using information sharing (at physical and data link layers)?
1.2. Research approach

The following steps are executed as research approach:

1. A literature study on the following topics is made: ETSI GeoNetworking, ETSI DCC, TPC, TRC, Radio Frequency (RF) channel modeling and simulation methodology.

2. The definition, implementation and test/evaluation of a small-scale basic simulation experiment then take place. Also part of this step is the design and implementation of a basic GeoNetworking subset (Single-Hop Broadcast) which refers to the type of transmission scheme among stations selected for this thesis report. We choose the open source network simulator ns-3 as simulation tool. The purpose of this activity is to get well acquainted with the simulation environment, define and implement statistics (performance metrics) and work towards a more detailed model description.

3. The next step is the development and assessment of improvements to ETSI DCC. This activity represents the core of the assignment. We implement four algorithms (two existing and two newly proposed) and we evaluate them based on the proposed performance metrics.

   • Existing algorithms
     a. Simple IEEE 802.11p with no transmit power control, included as a comparison basis to show network degradation under high channel load.
     b. ETSI DCC, included as a reference algorithm which aims for channel load control based on TRC and TPC.

   • Proposed algorithms
     a. TPC with simple proportional-integral (PI) control loop, which aims to alleviate the effects of high channel load on network performance based on TPC.
     b. TPC with proportional-integral (PI) control loop and exchange of channel load share information, which aims to alleviate the effects of high channel load on network performance based on TPC and information about neighbors.

1.3. Thesis report outline

The outline of the remainder of this thesis is as follows. Chapter 2 presents the literature study done about the history and features of wireless communications in the context of ITS, the necessity for channel load control, the characteristics of the ETSI DCC policy and the various works that have investigated TRC and TPC. This overview ends with an indication of the key open issues and a statement of contribution of the presented thesis research. Chapter 3 contains the ITS modeling and the simulation considerations. Chapter 4 describes the operation and characteristics of the existing and proposed algorithms. Chapter 5 contains the results of the simulations executed to evaluate and to compare the algorithms. We make an analysis of the benefits and drawbacks of each algorithm in this chapter. Chapter 6 concludes this report and presents the summary, contributions and possible future research topics related to this work.
2

LITERATURE STUDY

This section is intended to guide the reader through the research paths built around the concept of Intelligent Transport Systems (ITS) over the last decade. We have made emphasis on the European Telecommunications Standards Institute (ETSI) GeoNetworking specification and its components as the most suitable choice to support inter-vehicle wireless communications in the future. This chapter covers the background and importance of ITS in Section 2.1, presents an overview of the U.S. IEEE WAVE system in Section 2.2, the roadmap for standardization by ETSI TC ITS in Section 2.3, a description of the ETSI TC ITS protocol stack in Section 2.4, the GeoNetworking protocol and the necessity for Decentralized Congestion Control mechanisms in Sections 2.5 and 2.6, respectively. Finally Section 2.7 gives an overview of DCC-related literature, while Section 2.8 concludes this section, describing the focus of this project and specifying the approach for enhancements.

2.1. Background and importance of ITS

The evolution of humanity, especially in the last century, has been accompanied and enhanced by transportation systems (terrestrial, maritime and aero-spatial vehicles) which have benefited from the advances in technology fields like mechanics, electronics, telecommunications and several branches of manufacturing processes. In the case of terrestrial vehicles, the number of units has grown exponentially since combustion engines appeared while roads infrastructure has, in most countries, turned out insufficient or otherwise not suitable to handle such numbers. As a result, problems like roads congestion and waste of time/resources have emerged. Moreover, as the road speed limits have increased (as a consequence of combustion engines’ optimization), traffic accidents resulting in the loss of human lives or damage have become a major concern. The drivers’ unawareness and the lack of experience or time to react to road hazards represent important issues to tackle regarding road safety. In 2014, around 25,700 fatalities occurred in the EU at a rate of 51 deaths per million inhabitants [31].

In the beginning of the last decade, government and automotive industry bodies decided to start working on the next generation of transportation systems by trusting on Intelligent Transport Systems (ITS) as a possible solution. ITS refers to the ubiquitous use of ICT in transportation systems. Wireless communications are a key component of ITS (as are other technologies as radar, GPS, cruise control, etc.) that will be used to exchange information among vehicles, infrastructure (road-side traffic signaling elements) and personal devices in the near future. ITS aim to enhance transportation services by increasing safety, optimizing traffic flows, controlling CO2 emissions and facilitating e-commerce [28].

As described above, the problems induced by terrestrial vehicles (cars, truck, motorcycles, etc.) represent the major challenges nowadays but also offer an opportunity for applying technology. This led to focus the research efforts on vehicles and to adopt and investigate a specialization of ITS named Cooperative Intelligent Transport Systems (C-ITS).

In C-ITS, vehicles (usually called stations) communicate very frequently with each other in order to advertise their location and possible hazards detected on the road (typically within a range of around 1000 me-
Applications of C-ITS are classified, depending on their purpose, into four categories: vehicle-to-vehicle (V2V), vehicle-to-infrastructure (V2I) or infrastructure-to-vehicle (I2V), and infrastructure-to-infrastructure (I2I). The work presented in this thesis report will develop in the context of V2V wireless communications.

In practice, C-ITS research and testing have been conducted mainly in the U.S., Europe and Japan. In 1999, the U.S. Federal Communications Commission (FCC) officially allocated the spectrum at 5.850-5.925 GHz and named it as Dedicated Short Range Communications (DSRC). The FCC also issued strict rules for the DSRC spectrum in terms of channel usage and for the characteristics of the devices transmitting through it. In Europe, the Commission Decision “2008/671/EC” of August 5th, 2008 [27] determined the allocation for C-ITS of the frequency range 5.875 - 5.905 GHz. In Japan, the 7.0 GHz frequency band was selected for C-ITS.

In 2004, the corresponding wireless communications mechanisms for C-ITS were established in the IEEE 802.11p standard even though the physical medium was not officially established yet. The standard was derived as an amendment to the IEEE 802.11 standard widely known as the set of communication rules for Wireless Fidelity (WiFi) technology. IEEE 802.11p was finally integrated in the newest version: IEEE 802.11-2012.

Two system approaches evolved from IEEE 802.11p: 1) IEEE Wireless Access in Vehicular Environments (WAVE) in the U.S. and 2) European Telecommunications Standards Institute Technical Committee for ITS (ETSI TC ITS) in Europe. Both approaches detailed the corresponding protocol stacks (software implementation of the rules for operation) and inherited the layering concept of the well-known Open Systems Interconnection (OSI) architecture. This architecture splits any communication model into layers depending on the level of abstraction of information (electrical signals, bit, bytes, frames, packets, applications, etc.), enabling the development of network technologies (hardware or software) independently at each layer.

2.2. Overview of the U.S. IEEE WAVE system
In the U.S., the development of C-ITS evolved from the IEEE 802.11p and IEEE 1609 [38] standards (explained below) to the IEEE WAVE system as shown in Figure 2.1. In the U.S., DSRC is also known as IEEE 802.11p in reference to the lower layers of the architecture.

- IEEE 802.11p specifies Physical (PHY) and Medium Access Control (MAC) functionalities corresponding to the OSI layers 1 and 2 (physical and data link) and necessary for IEEE 802.11 devices to connect in a vehicular environment.
- IEEE 1609.4 specifies multichannel operation functionalities and relates to the OSI layer 2 (data link
2.3. The roadmap for standardization by ETSI TC ITS

One of the purposes of the European Commission (EC) is the implementation of the European Union policies. For that purpose, different departments known as Directorate-Generals (DGs) have been established. The DG for Mobility and Transport (MOVE) currently works on the following transport sub-groups [26]:

- European strategies
- Passenger rights
- Security Safety
- Clean transport, Urban transport
- Sustainable transport
- Infrastructure Connecting Europe
- Intelligent Transport Systems
- Research and Innovation
- International relations
- Public service obligations

Intelligent Transport Systems make use of information and communication technologies with the purpose to achieve efficient, clean, safe and seamless transportation services (rail, road, maritime and air vehicles).

The first step of the EC towards the adoption of ITS was the publication of the “Action Plan for the Deployment of Intelligent Transport Systems in Europe” on December 16th, 2008 [28]. This document stated the action area 4 named “Integration of the vehicle into the transport infrastructure” which defined architectures, plans, standards and mechanisms for I2I, V2I and V2V communications towards year 2014. Derived from this Action Plan, several projects funded by the EU began to establish the technological basis for C-ITS. The projects conduct a series of pilots to test emerging hardware and software for C-ITS. Drive C2X stands as a key project conformed by research and industry entities located across several EU countries [52]. The main contribution of Drive C2X is the test of C-ITS technologies via the installment of seven test sites in: Tampere (Finland), Gothenburg (Sweden), Helmond (Netherlands), Frankfurt (Germany), Yvelines (France), Vigo (Spain) and Brennero (Italy).

The second step was achieved by the publication of the Mandate M/453 EN named “Standardisation Mandate Addressed to CEN, CENELEC and ETSI in the Field of Information and Communication Technologies
to support the interoperability of Co-operative systems for Intelligent Transport in the European Community’ on October 6th, 2009 [29]. The Comité Européen de Normalisation (CEN) and the Comité Européen de Normalisation Électrotechnique (CENELEC) are well known European Committees created for technical standardization purposes. In a nutshell, this Mandate invited the European Standards Organizations ETSI, CEN and CENELEC to set the detailed standards for wireless communications in C-ITS. This document also encouraged the participation of different stakeholders who reflected the beneficial side for consumers, environment, workers, small and medium size companies, industry, toll providers and road infrastructure operators [6]. The resulting ideas or concepts derived from the related projects were also taken into consideration.

CEN and ETSI replied jointly [10] and accepted the Mandate M/453 on January 15th, 2010, by defining a work plan, specifying responsibilities and establishing the participation of different industry and research institutions. CENELEC replied by declining the invitation. In order to keep track of the work related to C-ITS, the following organizations interact with the CEN-ETSI group and have different responsibilities:

- European Union coordinates activities within the group.
- ITS-Steering Group (SG) monitors activities.
- Car2Car Communication Consortium (C2C-CC) and SafetyForum maintain cooperation activities.
- Diverse projects (Pre-drive C2X, Drive C2X, DITCM, CVIS, GST, Coopers, COMeSafety, Euro-FOT, GeoNet, SCORE@F, SafeSpot, Sevecom, SimTD, PRoVENT) execute pilot tests.
- ISO, IEEE, IETF, ARIB JP, ITU maintain International cooperation activities.

As the basis for the work of the CEN-ETSI group, two main inputs were taken into consideration:

1. The ITS reference model called Communication Access for Land Mobiles (CALM) [11]. The ISO CALM architecture was based on the layered OSI model and adapted for C-ITS, resulting in the structure shown in Figure 2.2 which later became as the ITS reference architecture:

![Figure 2.2: ISO CALM reference model [11].](image)

Table 2.1 describes the correspondence between the ISO CALM model [37] and the traditional OSI model [69]:

2. The concepts derived from the Car to Car Communication Consortium (C2C-CC). C2C-CC is an industry organization supported mostly by car manufacturers, who has provided the building mechanisms of operation of C-ITS containing the European vision. The document “Car to Car Communication Consortium Manifesto: Overview of the C2C-CC System”, published on August 28th, 2007 [9], described features as architectures, blocks, concepts, future applications, radio system, layer description, communication system and data security. Figure 2.3 represents the reference architecture visualized by the
Table 2.1: C-ITS CALM model features.

C2C-CC. This Figure depicts how vehicles will be equipped with hardware devices capable of exchanging messages with other vehicles and with the infrastructure along the road. Once the information from these vehicular networks reaches higher layers in the network, it will be possible to distribute it or use it accordingly in order to optimize vehicular road traffic:

From that point and forward, CEN defined the Technical Committee 278 (CEN/TC 278) and became responsible for standardization mainly at the application layer (but also with collaboration on the security and management layers), specifying features of C-ITS with data at a high level of abstraction (warnings, navigation, information from applications, etc.) and focusing on V2I and I2I approaches. On the other hand, ETSI established the Technical Committee ITS (ETSI TC ITS) and took the lead to work on the standards related to the access, networking transport and facilities layers, also with interaction with the other layers (management, security and applications) at a low level of abstraction of data (bits, frames, packets) and dictating the implementation of rules and protocols for transmission of safety messages.

In order to provide the necessary standards to cover the functions envisioned by the CALM reference model, ETSI TC ITS defined the following Working Groups (WGs) with specific targets to coordinate this major task:
- WG 1 – Application Requirements and Services
- WG 2 – Architecture and Cross Layer
- WG 3 – Transport and Network
- WG 4 – Media and Medium related
- WG 5 – Security

Finally, Special Task Forces (STFs) derived from the different WGs, emerged as the day-to-day producers of the C-ITS standards. The staff conforming the STFs was chosen from technical experts in the field, who eventually divide their working hours between the STFs’ tasks and their jobs at research institutes or the industry. Tables 2.2 and 2.3 correspond to the STFs related to C-ITS and their current status [17]. STFs 420 and 447 are relevant for this thesis project. STF 420 addressed aspects of the ISO CALM access layer as Decentralized Congestion Control (DCC) (described in Section 2.6) and multi-channel operations, resulting in the publication the technical specification ETSI TS 102 724 [18]. STF 447 aimed to develop the technical specification ETSI TS 102 636-4-2 [25] which describes DCC mechanisms at the network and transport layer when the access technology ITS-G5 is used.

<table>
<thead>
<tr>
<th>Code</th>
<th>Subject</th>
</tr>
</thead>
<tbody>
<tr>
<td>359</td>
<td>European profile standard for the physical and medium access layer of 5 GHz ITS systems.</td>
</tr>
<tr>
<td>365</td>
<td>Lower Layer Service Access Points Conformance Testing in support of Interoperability.</td>
</tr>
<tr>
<td>372</td>
<td>Conformance Testing and Interoperability DSRC.</td>
</tr>
<tr>
<td>395</td>
<td>Configuration and validation of channel congestion control methods of ITS.</td>
</tr>
<tr>
<td>398</td>
<td>Conformance and Interoperability Testing Framework for ITS.</td>
</tr>
<tr>
<td>404</td>
<td>Local Dynamic Map standardization scoping and classification/management of applications.</td>
</tr>
<tr>
<td>405</td>
<td>Conformance test specification for CAM &amp; DNM, GeoNetworking, Basic Transport Protocol and integration of IPv6 and GeoNetworking.</td>
</tr>
<tr>
<td>420</td>
<td>ITS G5 Channel Configuration, Channel selection, Link Layer Control, and interfaces between the Access Layer and Network &amp; Transport Layer.</td>
</tr>
<tr>
<td>421</td>
<td>G5 radio conformance testing in support of Interoperability.</td>
</tr>
<tr>
<td>422</td>
<td>Test suites for European Electronic Toll Service (EETS) and the ISO CALM FAST service.</td>
</tr>
<tr>
<td>423</td>
<td>Security standards to support ITS Work Programme.</td>
</tr>
<tr>
<td>424</td>
<td>Platform for Conformance Testing of Co-operative Awareness Messages (CAM), Decentralized environmental Notification Messages (DENM) and GeoNetworking Protocols (Section 2.4.3).</td>
</tr>
<tr>
<td>447</td>
<td>GeoNetworking media-dependent functionality for ITS-G5.</td>
</tr>
<tr>
<td>448</td>
<td>Local Dynamic Map (LDM) Standardization for vehicle ITS Station.</td>
</tr>
<tr>
<td>449</td>
<td>Maintenance of Test Specifications for CAM, DENM, BTP, GeoNetworking and IPv6 over GeoNetworking.</td>
</tr>
<tr>
<td>452</td>
<td>Extension of ITS Conformance Validation Framework with Security Test Specifications.</td>
</tr>
<tr>
<td>462</td>
<td>Maintenance of Conformance Validation Framework.</td>
</tr>
</tbody>
</table>

Table 2.2: List of finished C-ITS STFs.
2.4. Description of the ETSI TC ITS protocol stack

The ETSI TC ITS protocol stack was derived, as explained, from the ISO CALM reference model (Figure 2.2) containing six layers with the following characteristics as specified in ETSI EN 302 665 [20]:

- **Horizontal layers**
  - **Access layer**
    - Physical transmission (PHY) of bit streams through the physical medium.
    - Error free transmission of data frames over the physical medium with functionalities of medium access control (MAC) and logical link control (LLC).
  - **Networking and transport layer**
    - Definition of networking protocols: GeoNetworking (see Section 2.5), IPv6, others.
    - Definition of transport protocols for delivery of messages: UDP/TCP, dedicated ITS transport protocols, others.
    - Management of the joint layers.
  - **Facilities layer**
    - Session establishment between peer processes.
    - Formatting of data for presentation to the application layer.
    - Presentation of data and services to end users and to applications.
    - Support for Human Machine Interfaces (HMIs), data presentation, addressing, position, location, Co-operative Awareness Messages (CAM) & Decentralized Environmental Notification Messages (DENM) management.
  - **Applications layer**
    - Support for connection between C-ITS applications and communication tools via APIs.

- **Vertical layers**
  - **Security layer**
    - Control of intrusion detection, authentication, identity certificate, security information base, hardware security.
  - **Management layer**
    - Arrangement of functions for cross-interface management, inter-unit, networking, general congestion control, service advertisement, legacy system protection, management information base (MIB).

As we will explain later, the functions of the Access, Networking & Transport and Facilities layers, are relevant for this thesis project while Applications, Security and Management layers stay out of scope for this work. The characteristics of each layer are presented in more detail in the following subsections.
2.4.1. ITS Access layer

Often referred as ITS-G5, the Access layer (Figure 2.4) performs the functionality of the OSI physical and data link layers. The latter is subdivided into the Medium Access Control (MAC) and the Logical Link Control (LLC) sublayers for C-ITS. On the standardization side, the PHY and MAC layers for C-ITS are specified in IEEE 802.11p (already integrated in IEEE 802.11:2012) while the LLC is covered in ANSI/IEEE Std 802.2. For interconnection to other blocks (Figure 2.2), the ITS access layer (as other layers do) provides interfaces called Service Access Points (SAPs) which are sub named depending on the layers involved in the interconnection. For ITS access MI is used for connection to the Management layer while IN is used for connection to the Networking and Transport Layer. The SAP concept only serves as an informative functional specification.

According to ETSI EN-302-663 [21], for stations to be ITS-G5 compliant the following basic requirements must be fulfilled:

1. An orthogonal frequency division multiplexing (OFDM) scheme must be chosen as the transmission technology for the PHY layer.

2. The parameter ‘dot11OCBActivated’, part of the Management Information Base (MIB), must be set to ‘true’ to enable the functionalities of the MAC of the IEEE 802.11p. In general for IEEE 802.11 devices, two basic service sets (BSS) are available to group a set of stations: infrastructure BSS with centralized AP (BSS) and independent BSS (IBSS). The activation of the mentioned parameter enables the communication of stations in IBSS mode, also known as ad-hoc mode. IBSS allows transmissions between stations without centralized access points but with security and beaconing. The IBSS mode is already present in "plain" IEEE-802.11, i.e., without the p-amendment. In addition, the activation of the ITS-specific Outside the Context of a BSS (OCB) mode removes the needs for (de)association, authentication and beaconing.

3. LLC mode of operation must be set to Type 1 (unacknowledged connectionless mode).

4. The subnetwork access protocol (SNAP) must be present to distinguish between different network protocols.

As stated before, C-ITS in Europe operates in the 5.9 GHz frequency band which is split and called particularly as:

- ITS-G5A dedicated to safety applications (5.875 GHz – 5.905 GHz).
- ITS-G5B dedicated to non-safety applications (5.855 GHz – 5.875 GHz).
- ITS-G5C dedicated to RLAN (WLAN) communication between road side fixed stations and mobile stations (5.470 – 5.725 GHz).
2.4. DESCRIPTION OF THE ETSI TC ITS PROTOCOL STACK

- ITS-G5D dedicated to future ITS applications (5.905 – 5.925 GHz).

The allocated spectrum has been subdivided into the following channels:

<table>
<thead>
<tr>
<th>Channel type</th>
<th>Centre frequency</th>
<th>IEEE 802.11 channel number</th>
<th>Channel spacing</th>
<th>Default data rate</th>
<th>TX power limit</th>
<th>RX power density limit</th>
</tr>
</thead>
<tbody>
<tr>
<td>G5-CCH</td>
<td>5900 MHz</td>
<td>180</td>
<td>10 MHz</td>
<td>6 Mbps</td>
<td>33 dBm EIRP</td>
<td>23 dBm/MHz</td>
</tr>
<tr>
<td>G5-SCH2</td>
<td>5890 MHz</td>
<td>178</td>
<td>10 MHz</td>
<td>12 Mbps</td>
<td>23 dBm EIRP</td>
<td>13 dBm/MHz</td>
</tr>
<tr>
<td>G5-SCH1</td>
<td>5880 MHz</td>
<td>176</td>
<td>10 MHz</td>
<td>6 Mbps</td>
<td>33 dBm EIRP</td>
<td>23 dBm/MHz</td>
</tr>
<tr>
<td>G5-SCH3</td>
<td>5870 MHz</td>
<td>174</td>
<td>10 MHz</td>
<td>6 Mbps</td>
<td>23 dBm EIRP</td>
<td>13 dBm/MHz</td>
</tr>
<tr>
<td>G5-SCH4</td>
<td>5860 MHz</td>
<td>172</td>
<td>10 MHz</td>
<td>6 Mbps</td>
<td>0 dBm EIRP</td>
<td>-10 dBm/MHz</td>
</tr>
<tr>
<td>G5-SCH5</td>
<td>5850 MHz</td>
<td>182</td>
<td>10 MHz</td>
<td>6 Mbps</td>
<td>0 dBm EIRP</td>
<td>-10 dBm/MHz</td>
</tr>
<tr>
<td>G5-SCH6</td>
<td>5910 MHz</td>
<td>184</td>
<td>10 MHz</td>
<td>6 Mbps</td>
<td>0 dBm EIRP</td>
<td>-10 dBm/MHz</td>
</tr>
<tr>
<td>G5-SCH7</td>
<td>5470 to 5725 MHz</td>
<td>94 to 145</td>
<td>several</td>
<td>dependent on channel spacing</td>
<td>23 to 30 dBm EIRP</td>
<td>10 to 17 dBm/MHz</td>
</tr>
</tbody>
</table>

Table 2.4: ITS-G5 channel allocation characteristics [21].

Control channel (G5-CCH) and service channels (G5-SCH1 and G5-SCH2) are reserved for safety applications over ITS-G5A.

2.4.2. ITS Networking Transport Layer

This layer, as its name suggests, subdivides its functionalities into two kind of protocols (divided per sublayer by the dotted line in Figure 2.5 as specified in ETSI TS 102 636-3 [22]). The Networking sublayer protocols assume the task of data routing from source to destination stations in a given geographical area. The Transport sublayer protocols deal with end-to-end delivery of data based on the requirements of higher layers (ITS Facilities and Applications) plus the reliable data transfer, flow control and congestion avoidance.

![ITS Networking Transport layer architecture](image)

At the Networking sublayer, the GeoNetworking protocol emerges as the main mechanism for data routing based on geographical addressing and forwarding. Its services can be accessed by other protocol entities located at the Facilities layer via the Basic Transport Protocol (BTP), the main protocol at the Transport sublayer. BTP has a 4-byte protocol header residing on top of GeoNetworking and provides: end-to-end, connectionless transport service and minimal transport service. BTP also provides multiplexing and de-multiplexing of ITS Facilities layer messages and also delivers the data packets (transported by the GeoNetworking protocol) to the mentioned layer.

As shown in Figure 2.6, other protocols like TCP, UDP and IPv6 (IPv4) reside at the ITS Networking and Transport layer to expand the functionalities and services offered to upper (ITS Facilities) and lower layers (ITS Access). Moreover, ETSI also specified in ETSI TS 102 636-3 [22] the interactions between those protocols, as visualized in Figure 2.6.
As shown in Figure 2.6, IPv6 is an important part of the ITS layer because it will allow the transmission of data packets between GeoNetworking-based and IP-based stations. IPv6 will allow functions as on board internet access, transmission of safety messages to remote traffic control rooms or to farther located stations, etc. Figure 2.6 also shows that the final goal of the ITS Networking and Transport layer is to act as the bridge between the ITS Access and ITS Facilities layers which can be achieved by running GeoNetworking on top of ITS Access technologies, specifically ITS-G5. Other options are to run IPv6 over GeoNetworking or IPv6 directly on ITS Access technologies, e.g. ITS-G5, WiFi, Bluetooth, 2G/3G/4G or Ethernet.

2.4.3. ITS Facilities Layer
The ITS Facilities layer offers services to support C-ITS applications by implementing the functionalities of the OSI-based application, presentation and session layers. This layer handles functions like application, information, communication, session support and management of the facilities layer as depicted in Figure 2.7:

As mentioned in ETSI EN 302 665 [20], the ITS Facilities layer provides data structures to handle and administrate information of different types and sources. It offers data presentation, addressing and position/time support, among other functionalities. Moreover, one of the core features of this layer is the support for the transmission of road-safety messages: Cooperative Awareness Messages (CAMs) and Decentralized Environmental Notification Messages (DENMs):
• CAMs, the basic unit of C-ITS, are periodically sent among stations at a given frequency satisfying the requirements of the application and transport and network layers. CAMs contain the vehicle’s driving state (position, speed, heading, etc.) or the basic status of a roadside unit [6]. Their frequency relies, among others, on the wireless channel load.

• DENMs, also sent among C-ITS stations, are event-driven messages triggered by the detection of informative or hazardous road events, e.g. hard braking [6]. These messages are transmitted and retransmitted based on their importance and the rules set by a given safety application.

2.4.4. Cross layer DCC functionality
For most wireless technologies, a high channel load negatively impacts the performance of their communication systems. For C-ITS, sufficient channel performance is crucial for road safety. As it will be addressed in Section 2.6, the necessity of channel load reduction lead to the development of a Decentralized Congestion Control (DCC) framework by ETSI. For this thesis, it is sufficient to notice that DCC has components which operate at different layers of the ETSI TC ITS architecture. Those components execute DCC by controlling the following parameters that modify the flow of safety in a C-ITS environment as explained in Section 2.6.3: Transmit Power Control (TPC), DCC Sensitivity Control (DSC), Transmit Rate Control (TRC), Transmit Data Rate Control (TDC) and Transmit Access Control (TAC).

2.5. GeoNetworking protocol
As developed in ETSI TC ITS WG3 and the GeoNet project, the GeoNetworking protocol (part of the Networking and Transport layer) will support the core communications of C-ITS in Europe for V2V, V2I and I2V communications. One the main objectives of GeoNetworking is the reliable dissemination of data packets, e.g., safety and non-safety, among interested stations. Figure 2.8, published in [9] shows a practical application of GeoNetworking for transmission of DENMs where station A detects icy road and advertises this information to the vehicles inside and outside its geographical region. In this example station (vehicle) A transmits a DENM packet to inform other stations about the hazard.

Transmission in this example can be classified in short and long range. For the short range, station A transmit this message to station B and to remote side unit (RSU) 1 in a one hop scheme assuming that only this two stations are inside its physical transmission range. Station B then retransmits the message to station C also in a one hop scheme. For the long range RSU 1 also retransmits the message to central station (control centre) via other long range wireless technologies. The control centre distributes this message according to its relevance for other stations and decides to deliver it to RSU 2. Finally the message is transmitted to the stations inside the transmission range of RSU 2, i.e. stations D, E and F. In this manner, every station which receives this message (in the short and long range) become aware of the hazard and are able to take safety decisions.

Only short range transmissions based in one or multiple hop transmissions are subject of this thesis work and are therefore detailed below.

GeoNetworking protocol offers two basic features to support C-ITS applications:

• Ad-hoc connectivity. Mobile Ad-Hoc Networks (MANETs) have been extended to Vehicular Ad-Hoc Networks (VANETs) for V2V communications in which no central access points are needed for connectivity among mobile stations. The term ‘Ad-hoc’ refers to the capability of communication without any centralized infrastructure. The concept of VANETs has been adopted implicitly in the context of C-ITS.

• Geographical information (addressing method). For any (wired or wireless) network system, addressing is compulsory and refers to the mapping of every station with a unique ID which allows the correct routing of data between sending and receiving stations. For typical (wired or) wireless networks, Internet Protocol (IP) addressing is the usual method to uniquely identify stations with 32-bit numbers (IPv4) or 128-bit numbers (IPv6). VANETs rely on the geographical location of stations as addressing mode supported by mechanisms like Global Positioning Systems (GPS).
The use of geographical information as addressing mode lead to the subdivision of the GeoNetworking concept into [9]:

1. Geographical addressing. Geographical locations in C-ITS are intended for two purposes: a) to correlate the identity of stations to their physical position and b) to define geographical regions which are linked to one, any or all stations within a specified region. This addressing mode requires the periodical refresh of the geographical addresses because of the mobile nature of stations in vehicular scenarios. Moreover, every geographical address must be related to a time stamp to verify its validity and usefulness for safety applications. The number of stations and their location inside a geographical region can also change over time and need to be as up to date as possible.

2. Geographical routing. Forwarding algorithms are needed to send data packets to a given station based on its geographical address and its location within a certain region. In this context, GeoNetworking establishes four forwarding modes (S = source station, F = forwarding station, D = destination):

   a. Geographical unicast, used to directly communicate a single source station with a single destination station. This communication can be direct or achieved by hopping over one or more intermediate stations.

   b. Topological-Scoped Broadcast (TSB), specialized on the transmissions of data packets from a single source station to all the nodes inside the previously scoped network, defined at the data link layer. TSB can be also sub classified depending on the number of hops selected for transmissions. One-hop broadcast is the simplest mode of TSB in which stations broadcast messages only to their neighbors at one hop distance. Figure 2.10 exemplifies a two hop TSB.
c. Geographically-scoped broadcast, intended for transmissions from a single source station to all the nodes inside a given geographical region. In this scheme two options are available:
   i. Source station inside the target geographical region.

   ![Figure 2.11: Geographically-scoped broadcast (source inside region)](image)

   ii. Source station outside the target geographical region.

   ![Figure 2.12: Geographically-scoped broadcast (source outside region)](image)

d. Geographically-scoped anycast, used for transmissions from a single source station to any of the destination stations inside the targeted area. In this case the forwarding of data packets to all the nodes inside the region does not occur, instead, the process finishes at the time one destination station is reached.

Apart from these forwarding algorithms, two routing algorithms (for Geographical unicast or anycast) are marked as relevant for GeoNetworking in the literature:

- **Greedy Forwarding** establishes that in a forwarding process, based on the geographical location of stations, the next hop is selected by considering only the station with the smallest distance to the destination until this is reached.

- **Contention-Based Forwarding** allows the packet to be broadcasted to all the neighbors of the next hop station and then buffered by each of them. At each listening station a timer, determined by the distance from the current station to the destination, is decreased until reaching a zero value. At this point the considered station decides to rebroadcast the packet only if it has not received a duplicate from one of its own neighbors. The purpose is to reduce the number of expected transmissions.
From the standardization point of view, ETSI TC ITS WG3 has developed several technical specifications (TS) documents, under the series ETSI TS 102 636, describing the GeoNetworking protocol together with other TS defining useful features of the C-ITS architecture. Several of these TS have already been established as national standards and made available as European Standards (EN) under the series ETSI EN 302 636 and others.

As explained earlier, GeoNetworking is intended to run physically over ITS-G5 but also over other technologies e.g. WiFi. For that reason, the specifications have taken into account the scenarios for media-independent (ETSI TS-102-636-4-1) [23] and ITS-G5 media-dependent (ETSI TS-102-636-4-2) [25] functionalities. By the time of closure of this report only the document specifying the media independent functionality has been converted into an EN document (ETSI EN-302-636-4-1). The ITS-G5 media-dependent specification expands the former by adding two characteristics:

• The adoption of Decentralized Congestion Control (DCC) as a cross layer function. The foundations of the DCC framework and the component for DCC at the Access Layer have been specified in ETSI TS 102 687 [24] while the specifications of DCC for the ITS Networking Transporting, Facilities and Management layers are still in progress.

• The support for Multi-channel Operation (MO) with some standards developed:
  – Service announcement messages (TS 102 890-2) [19] providing support for general information exchange based on the IEEE 1609 standards.
  – Channel specifications for ITS-G5 (TS 102 724) [18] focused on routing different communication traffic streams to different channels, depending on the current congestion states of those channels.

2.6. Decentralized Congestion Control

2.6.1. Basic concepts related to DCC

The concepts explained in this subsection are useful to understand the fundamentals of DCC mechanisms.

**JUSTIFICATION FOR CONGESTION CONTROL**

Channel congestion, can be defined as the perception of the medium’s status (e.g. IDLE, BUSY) in a given period of time and sensed by any station present in a given network. It can be measured in terms of channel load and behave according to the number of intended transmissions. High channel load values have a negative impact on network metrics like end to end delay, throughput, packet loss, ratio of transmitted/received packets, etc. For C-ITS, the packets are referred to CAMs and DENMs.

The effects of channel congestion are intensified by the well-known hidden and exposed terminal problems which are present in wireless networks even if congestion does not occur. The hidden terminal problem refers to stations’ communication ranges overlapped in such a way that they are reachable to some stations and unreachable for others, leading to collisions. Figure 2.13 shows that station B is located within the range of stations A and C while these are out each other’s range. The problem arises when an ongoing transmission between station A and station B is not sensed by station C. If a new transmission between station C and station B is initiated then a collision will occur.

![Figure 2.13: Hidden terminal problem.](image-url)
2.6. Decentralized Congestion Control

The exposed terminal problem appears when ongoing transmissions between some given stations prevent new transmissions between other stations to start, even if both transmissions would not interfere physically. This case leads to an underutilization of the network capacity as simultaneous transmissions are prevented to coexist. Figure 2.14 exemplifies this problem. Station S1 senses stations R1 and S2 only while station S2 senses stations S1 and R2 only. The ongoing transmission between S1 and R1 is heard by S2 who wants to start a new transmission with R2 during the same period of time. Because R1 is out of its range, S2 decides to delay or cancel the new transmission even if it would not collide with the existing transmission.

![Exposed terminal problem](image)

Figure 2.14: Exposed terminal problem.

Both hidden and exposed terminal problems intensify the congestion of the communication channel. The contribution of the hidden stations is intuitive because an increased number of collisions might lead to retransmissions and possibly to new collisions decreasing the channel performance. For exposed stations the problem is stated as a sub utilization of the channel. However mechanisms to decrease its effects (and the effects of hidden stations) have been developed as it will be explained below. These mechanisms also contribute with overhead in detriment of the channel's performance.

Medium Access Control (MAC)
As mentioned before, the C-ITS stations transmitting in the 5.9 GHz frequency band make use of the communications mechanisms standardized in IEEE 802.11p and also supported by the functionalities of a PHY and a MAC sublayer.

In general, the MAC sublayer is responsible to keep the access to the communication channel as fair as possible for the stations sharing it. In order to achieve this goal IEEE 802.11p specifies the use of the Enhanced Distributed Channel Access (EDCA) as MAC method which is based on the Distributed Coordination Function (DCF) [5]. Channel monitoring is key for MAC mechanisms because it allows to sense if the medium is occupied. Clear Channel Assessment (CCA) is used for channel monitoring and can be achieved in two ways:

- Physical carrier sense, a procedure that performs energy detection (ED) by measuring the energy in the target frequency range and carrier sense (CS) by recognizing the frames on the air, directly on the physical medium.
- Virtual carrier sense via Network Allocation Vector (NAV), a value set at MAC header level which indicates the period of time that the channel is reserved for an ongoing transmission and therefore prevents other listening stations, sharing the medium, from using the channel during that period of time.

Distributed Coordination Function (DCF)
Distributed Coordination Function (DCF) is a well-known protocol for wireless networks that uses CSMA/CA (a channel sense - before transmitting technique) to implement a procedure for carrier sensing and prevent data packet collisions [5]. DCF protocol has been developed to alleviate the effects of the hidden and exposed terminal problems of wireless networks benefiting C-ITS applications as well. DCF has two derivations:

- DCF - Basic access mode. This mode relies on the physical carrier sense and is illustrated in Figure 2.15. A given station transmitting in this mode makes use of CS to sense the channel state. If the channel is idle for a period of time Distributed Interframe Space (DIFS) the station is clear for immediate transmission. If the channel is busy, the station must wait until the channel is idle at least for a DIFS period. Afterwards, the station must perform a backoff procedure based on a timer computed from a
predetermined content window (CW) and a slot time from the PHY layer. This timer is decremented only when the channel is idle and only when it reaches a zero value, the station is allowed to transmit. If it happens that the channel is sensed again as busy during this procedure, the timer will be frozen until the channel is idle again to continue with the process.

Figure 2.15: DCF - Basic access mode [8].

- DCF - RTS/CTS access mode. This mode is a variation of the DCF basic access mode and makes use of the physical and virtual carrier sense. As shown in Figure 2.16 this mechanism employs a four-way handshaking technique based on flag messages called request to send (RTS), clear to send (CTS) and acknowledgment (ACK). In a similar way as the basic mode, a station which desires to transmit must sense an idle channel for at least a DIFS period. If the channel is idle, the station sends an RTS message to the destination station instead of transmitting immediately. The destination station responds, after a short inter frame space (SIFS) period, with a CTS message. After a correct reception of the CTS message, the former station is allowed to transmit the desired frame. Once the transmission is complete the destination station responds with a confirmation ACK message. RTS and CTS messages contain information about the length of the frame before its transmission takes place. Other listening stations that receive these RTS and CTS messages are then able to use this information to set a decrementing NAV counter to defer for transmission. After the NAV counter reaches zero and the channel is sensed as idle for a DIFS period those other stations start a backoff procedure before trying to transmit.

Figure 2.16: DCF - RTS/CTS access mode [8].
In general the backoff time is selected based on the following formula 2.1:

\[
\text{backoff time} = \text{random()} \times \text{slottime},
\]  

where \(\text{random()}\) is a pseudo-random integer drawn from a uniform distribution over the interval \([0, CW-1]\), where \(CW\) takes values initially from \(CW_{\text{min}}\) or doubled at every failed transmission until reaching \(CW_{\text{max}}\) and reset to \(CW_{\text{min}}\) after a successful transmission; \(\text{slottime}\) is the slot duration.

For broadcast/multicast transmissions the RTS-CTS-ACK approach is not applicable. Instead a back off procedure is executed in case the medium is sensed as busy within DIFS. Basically a subset of the RTS/CTS/ACK operations happen afterwards: a number is drawn and then decreased every slot the medium is sensed idle. Once the counter reaches zero the frame is transmitted.

**Enhanced Distributed Channel Access (EDCA)**

EDCA is an optimized version of the basic IEEE 802.11 DCF protocol and supports service differentiation by assigning eight different user priorities (UPs) mapped into four access categories (ACs): voice, video, best effort and background (Table 2.5). This differentiation mechanism allows prioritization of traffic flows which is useful for VANETs (transmissions of CAMs and DENMs).

<table>
<thead>
<tr>
<th>Priority</th>
<th>UP</th>
<th>802.11 designation</th>
<th>AC</th>
<th>Designation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Lowest</td>
<td>1</td>
<td>BK</td>
<td>AC-BK</td>
<td>Background</td>
</tr>
<tr>
<td></td>
<td>2</td>
<td>-</td>
<td>AC-BK</td>
<td>Background</td>
</tr>
<tr>
<td></td>
<td>0</td>
<td>BE</td>
<td>AC-BE</td>
<td>Best effort</td>
</tr>
<tr>
<td></td>
<td>3</td>
<td>EE</td>
<td>AC-BE</td>
<td>Best effort</td>
</tr>
<tr>
<td></td>
<td>4</td>
<td>CL</td>
<td>AC-VI</td>
<td>Video</td>
</tr>
<tr>
<td></td>
<td>5</td>
<td>VI</td>
<td>AC-VI</td>
<td>Video</td>
</tr>
<tr>
<td></td>
<td>6</td>
<td>VO</td>
<td>AC-VO</td>
<td>Voice</td>
</tr>
<tr>
<td>Highest</td>
<td>7</td>
<td>NC</td>
<td>AC-VO</td>
<td>Voice</td>
</tr>
</tbody>
</table>

Table 2.5: UP to AC mappings in EDCA [8].

The main difference between the basic and optimized version of DCF relies on the replacement of the Distributed Inter Frame Spacing (DIFS) parameter with the Arbitration Inter Frame Spacing (AIFS) parameter which adds Quality of Service (QoS) functionality (required for IEEE 802.11p). AIFS is the time (distinct for different ACs) that the channel is sensed before randomly extracting the backoff or transmitting the data frame and calculated as:

\[
\text{AIFS}[\text{AC}] = \text{SIFSTime} + \text{AIFSN}[\text{AC}] \times \text{Slottime},
\]  

where \(AIFSN[\text{AC}]\) is an integer AIFS number assigned to each AC and is shorter as the AC has a higher priority, allowing for shorter waiting periods. In EDCA, \(CW_{\text{min}}\) and \(CW_{\text{max}}\) are also variable depending on the AC priority. Collisions within a station are resolved internally by assigning the transmit opportunity (TXOP) to frames with the higher priority AC and setting a virtual collision (interpreted as an external collision) for the frames with lower priority ACs. TXOP is the time interval during a frame separated by a SIFS is transmitted. The main 802.11p MAC parameters are reported in Table 2.6.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>(CW_{\text{min}})</td>
<td>15</td>
</tr>
<tr>
<td>(CW_{\text{max}})</td>
<td>1023</td>
</tr>
<tr>
<td>Slot Time</td>
<td>(13,\mu\text{s})</td>
</tr>
<tr>
<td>Slot Time</td>
<td>(32,\mu\text{s})</td>
</tr>
</tbody>
</table>

Table 2.6: Main 802.11p MAC parameters [8].
2.6.2. ETSI TC DCC architecture and components

The main objectives of DCC, according to ETSI TS 102 687 [24], are to maintain network stability, throughput efficiency and fair resource allocation for ITS G5 stations operating in the ITS-G5A and ITS-G5B frequency bands. The purpose is to keep VANETs (supporting C-ITS applications) running as stable and collision-free as possible in order to support critical road safety applications. In the context of C-ITS saturated communications channels might lead to life threatening situations on the roads. Figure 2.17 illustrates the DCC components and their location in the ETSI TC ITS architecture.

Specifically, DCC is intended to comply with a set of operational requirements: to achieve fair allocation of resources and channel access ITS stations, keep channel load between certain thresholds, reserve communication resources for high priority messages (DENMs), provide fast adoption to a changing environment, keep limited oscillations in the control loops, comply to specific system requirements. High channel load values are not desired as it would imply a high number of collisions of messages. However, too low channel load values are not meaningful as they represent the case in which fewer messages than the transmission medium would support are transmitted through a certain network. For safety reason, one of the targets for VANETS is to maintain the amount of successfully transmitted messages as high as possible. As it will be later explained in subsequent chapters, channel load is directly related to the transmission power values and therefore to the transmission range of ITS stations. Therefore, lowering the transmission ranges of stations towards nearly zero values would isolate a given station from the rest of stations in the network.

![Figure 2.17: ETSI DCC architecture [24].](image)

2.6.3. ETSI DCC Access Layer

ETSI established the architecture of the DCC Access layer, showed in Figure 2.18, to describe a functional approach based on blocks from which the control loop block distinguishes as the main block. The purpose of each block is stated as follows:

- Transmit queuing. Implements the functionalities of IEEE 802.11 queues.
- Channel probing. Collects statistics of the communication channel.
- Transmit statistics. Collects information about the stations’ transmissions.
- Control loop. Adapts the behavior of the station to achieve an acceptable channel load level.

The functionality of the control loop block is based on the philosophy of classical control theory systems utilizing a feedback value to reach a desired output value. Inside this block, the following mechanisms have been established to control channel congestion:
• **Transmit power control (TPC)**, controlling the range of stations based on the power utilized for transmissions.

• **Transmit rate control (TRC)**, controlling the interval of time between transmitted packets.

• **Transmit data rate control (TDC)**, managing the data rate of transmissions.

• **DCC Sensitivity Control (DSC)**, adapting the CCA sensitivity threshold that flags a channel as busy during packet reception.

• **Transmit Access Control (TAC)**, prioritizing packets by setting up a transmit queue.

• **Multiple channel operation**, making use of different transmission channels.

---

The ‘Control loop’ block is fed with the channel load (CL) value obtained via the ‘Channel probing’ block and the statistics of packet transmissions (packet arrival rate, packet average duration, signal average power and cumulative channel use) gathered by the ‘Transmit statistics’ block. With this information the ‘Control loop’ block manages the following parameters based on the selected mechanism: transmit power (TPC), inter-packet transmission interval (TRC), data rate (TDC), CCA sensitivity threshold (DSC) and transmit queue status (TAC). The control loop utilizes the Network Design Limits (NDL) as the reference values to compare with the sensed values. The NDL are stored in the NDL database which is maintained at the DCC management layer.

As stated before, the main goal of the ETSI DCC control loop mechanisms is to keep the channel load between reference NDL values: MinChannelLoad and MaxChannelLoad. For this purpose, this entity relies on a three state machine (RELAXED, ACTIVE and RESTRICTIVE) which classifies the CL value observed by a given station. Figure 2.19 shows the relationship among the states of the DCC control loop. A given station implementing this state machine initializes in ‘RELAXED’ state and switches to/from ‘ACTIVE’ and ‘RESTRICTIVE’ states depending on the measured CL value in comparison with the NDL values as shown in this figure. In Chapter 4 we will present a detailed explanation of the mechanisms considered for state transitions and the transmission parameters utilized by stations depending on the current state.

ETSI DCC control loop allows the configuration of n sub-states for the ‘ACTIVE’ state for more fine-grained control as depicted in Figure 2.20. In this example, the number of ‘ACTIVE’ states has been set to 2. With this sub-items it is possible to configure more TX power and inter-message values adding more steps to the switching process.
2.7. Overview of DCC-related literature

The research on DCC has triggered several ideas to optimize the main mechanisms. From those mechanisms TPC and TRC are raised as the most promising and therefore most studied during the last decade.

The justification for TPC is evident because the transmission range of stations (area covered by stations) can be controlled by adjusting the transmission power. The use of higher transmission power increases the transmission range of a given station and also reduces the hops or retransmissions that a message needs to reach its intended destination. However an increase of the transmission range comes at the price of increasing collisions and congestion because the hidden and exposes node problems are augmented. With this in mind, the level of congestion can be directly impacted (positively or negatively) by selecting a given power value in a particular scenario. The solutions towards TPC are classified based on their appearance in three main categories: 1) implementing TPC on a per node, per link or per set of nodes basis to control the network connectivity, 2) utilizing power aware schemes based on routing algorithms with power as metric; or 3) modifying the MAC layer.

From this classification the following works on TPC are noted as important. The first solutions investigated the feasibility of power control by taking advantage of features of routing protocols as proposed by Singh et al. [55] or by adjusting parameters at the physical and data link layers as proposed by Subbarao [57] and Dube et al. [14]. Ramanathan et al. [50] looked into finding a unique power level for every station in the network while Elbatt et al. [16] focused into controlling metrics like end-to-end throughput by adjusting power. Gupta et al. [33] stated that the reduction of power levels showed improvements for channel load in scenarios where transmissions based on small hops were preferred over those based on long hops. Wattenhofer et al. [64] proposed that moving stations increased their power levels until finding a neighbor at a certain distance. At those early stages, Monks et al. [45] researchers started to look into solutions at the MAC layer to control power. Xu et al. [67] and Chen et al. [12] suggested the activation of sleep mode on interfering nodes.

Based on those works, three TPC solutions for MANETs appeared and remained as the most remarkable.
The Common Power (COMPOW) algorithm, introduced by Narayanaswamy et al. [48], proposed a network layer based (with routing agents) protocol with an asynchronous, distributed and adaptive approach based on finding the smallest common power level, sufficient to keep the entire network connected. However, the authors themselves detected possible scenarios where clustered stations lead to unnecessary use of high power levels. An extension of COMPOW was represented by the joint clustering/TPC CLUSTERPOW algorithm, presented by Kawadia et al. [39] for which stations individually run a distributed algorithm to choose the minimum power level (that can be different for every station) to reach the destination. Finally, Muqattash et al. [47] proposed the POWMAC protocol an approach that allows certain levels of maximum tolerable interference (MTI) at the receivers. Based on this mechanism, POWMAC adjusts the transmission power of data packets of possible interfering stations instead of shutting down those transmissions. Unlike COMPOW and CLUSTERPOW, POWMAC requires fundamental changes to the MAC protocol using an access window (AW) to allow RTS/CTS exchanges occurring before data packet transmissions.

Once the concept of C-ITS became mature over the past five years, efforts towards congestion control in vehicular scenarios were directly addressed based on TPC, TRC and joint solutions. Later, congestion control solutions were classified as reactive (addressing congestion as it appears) and proactive (preventing congestion by predicting it). The Distributed Fair Power Adjustment for Vehicular environments (D-FPAV) protocol, developed by Torrent-Moreno et al. [60], implemented a proactive transmit power adaptation based on cooperative calculation of power levels. Huang et al. [35] introduced another protocol that aimed for a Channel Busy Ratio (CBR) (channel load) threshold, the fraction of time that the channel is sensed as busy, by determining the minimum transmit rate of stations. Schmidt et al. [51] addressed the effects of hidden stations on network performance and derived a model based on adjusting the channel load. This work proposed rate adaptation on a per-packet basis using the Channel Busy Time (CBT) as a metric. Later joint rate/power solutions proposed fractioned resource assignment as stated by Baldessari et al. [2], contextual congestion control as proposed by Sepulcre et al. [53] and transmit rate regulation at MAC level based on CBR values as stated by He et al. [34]. Khorakhun et al. [40] also adapted transmission power based on the comparison of the CBR value against a given threshold. This idea was further extended by SOURC, presented by Busche et al. [7] which added 2-hop piggybacking and a min-max threshold.

The protocols Periodically Updated Load Sensitive Adaptive Rate control (PULSAR) developed by Tielert et al. [59] and Linear Message Rate Integrated Control (LIMERIC), introduced by Bansal et al. [3] represent important steps into congestion control and are part of the focus of this work. Both protocols are under evaluation to be part of the ETSI TC ITS architecture given their effectiveness for channel load control as stated by Sepulcre et al. [54] which recently introduced Integration of Congestion and Awareness control (INTERN), a protocol integrating channel congestion and neighbor awareness control. LIMERIC and PULSAR maintain the channel load under a set threshold independently of the density of stations. For them, channel load can be measured in terms of CBR. Bansal et al. [4] states that LIMERIC adapts the packet transmission frequency of each vehicle based on a target channel load level and the channel load locally measured. PULSAR adapts the packet transmission frequency of each station by considering not only the locally sensed CBR but also the CBR sensed by its neighbors [59]. With that information, PULSAR determines the maximum congestion level and increases or decreases the rate using the principle of Additive Increase and Multiplicative Decrease (AIMD).

2.8. Focus of this project

Despite the advances towards congestion control in C-ITS achieved by ETSI ITS DCC framework and proposals like LIMERIC and PULSAR, there is still room for improvement before reaching a definite solution. An efficient congestion control scheme will certainly lead to a faster deployment of C-ITS applications in the near future.

ETSI ITS DCC has demonstrated the reduction in congestion control mainly through the TRC and TPC mechanisms. However it has been documented by Bansal et al. [4] that this approach has an oscillatory and unstable behavior caused by its discrete states. Vesco et al. [63] show that TRC is the only contributing mechanism for congestion control while TPC or joint TPR/TPC solutions might even degrade the network performance in vehicular and in urban scenarios. For Autolitano et al. [1] the DCC scheme has proven to be highly sensitive to the timing and channel load parameters settings. Wrongly chosen parameters contribute
2. Literature study

As stated before, LIMERIC and PULSAR have shown enough improvement in congestion control to be considered as part of ETSI ITS DCC. However, according to the studies of Egea-Lopez et al. [15] both approaches lack of a solid scheme regarding fairness. It also claims that LIMERIC converges to a certain rate for every station which is suboptimal by design and only applicable to one-hop transmissions. In turn PULSAR is said to require synchronization information from two-hop stations in order to achieve improvements. This work also evaluates the joint LIMERIC+PULSAR approach and concludes that it presents an oscillating behavior. Moreover, their cross layer functionality affects the operation of the ETSI ITS Facilities, the Networking (GeoNetworking) and the Access layers.

Performance evaluation and improvement of ETSI GeoNetworking in combination with the DCC policy is the main focus of this project. This thesis work presents two solutions for DCC based on Transmit Power Control that will aim to enhance the control loop block proposed by the ETSI ITS DCC at its Access layer (Section 2.6.3). In contrast to the DCC solution, our proposed TPC solutions rely on driving channel load values to a reference value instead of keeping it between predefined boundaries. This feature aims to eliminate the oscillations adversely caused by the ETSI DCC mechanisms. Both proposed solutions look for the implementation of simpler channel load controllers inspired by classical process control theory (Proportional-Integral control). The ideas presented in this thesis work focus on the use of TPC to control channel load values and consequently enhance the performance of the network in terms for example of successfully received packets. We aim to prove that the use of only TPC will suffice to enhance the performance of ETSI ITS DCC approach which makes use of both TPC and TRC to maintain channel load between set boundaries. In addition, one of our solutions assesses the usefulness of information about the neighborhood of a given station to determine the level of contribution of that station to the overall channel load.
This chapter describes the system model selected to simulate an ITS scenario suitable to test the algorithms presented in this thesis work. Section 3.1 covers the characteristics of the environment, Section 3.2 states the assumptions on TPC, Section 3.3 expands on the emulation of CAMs, Section 3.4 details the dissemination of CAMs. Finally, Section 3.5 presents the mobility scenarios and Section 3.6 presents the simulation tools.

We choose simulation studies as our means for evaluating the performance of wireless communications in ITS. As the purpose of C-ITS technologies is to control and enhance the behavior of vehicular traffic flows, it is often desirable for researchers to test hardware equipment and software algorithms on real vehicles and roads. However, those scenarios are clearly not feasible to reproduce at least in the research phase, due to the huge required amount of financial and infrastructure resources as the systems scale up. We therefore (have to) resort to simulation at this stage.

In order to obtain useful data from ITS simulations, it is important to select meaningful scenarios bounded in terms of space and time. The number of possible vehicular traffic scenarios is obviously too large to consider exhaustively. For all practical purposes, there is an infinite number of combinations possible from setting the number of vehicles and the traffic flows, which leads to difficulties in simulation studies, despite the current available simulation techniques and software tools. This chapter is therefore concerned with the selection of appropriate scenarios, and with motivating our selection.

Another key requirement is the selection of the network control parameters (individual and system). In the case of individual network parameters we decided to align with the selection made by the author group of ETSI DCC in order to obtain meaningful results for the evaluation of the algorithms proposed by that group and for the comparison with the proposed algorithms by this thesis work. As individual network control parameters we refer for example to the transmission power values and inter message times selected by stations for data transmission within a given network. In the case of system network parameters, i.e. network topology and electromagnetic wave propagation model, we chose for simple models to lower the complexity of the simulations setup. This chapter gives a detailed explanation on the selection and assumptions we took for this thesis project.

3.1. Characteristics of the environment
We restrict ourselves to an open space and highway environment as the simulation environment of this research work. Only traffic flowing in one-direction is considered, with vehicles placed in a straight line as depicted in Figure 3.1. We select such environment in pursuit of achieving the minimum scenario where the essence of the channel load problem can be isolated and analyzed. We exclude environments with multiple lanes and two way vehicular traffic as it would make the simulations overly complex and time-consuming. In order to obtain more realistic results, we consider scenarios with static and mobile vehicles in order to
evaluate the benefits and drawbacks of the existing and proposed algorithms. In the case of mobile scenarios, we use the Intelligent Driver Model (IDM) as car-following model which will be detailed in Section 3.2.5. Overtaking maneuvers and effects of Doppler shifts (all vehicles move in the same direction with only limited speed differences) are not considered.

The presence of vegetation, buildings and infrastructure at roadsides are not considered as relevant for this thesis work.

We select vehicle to vehicle (V2V) communication type for the message exchange among vehicles within this scenario while vehicle-to-infrastructure (V2I) or infrastructure-to-vehicle (I2V), and infrastructure-to-infrastructure (I2I) communication schemes are not considered. V2V is the most important communication type in the context of VANETs as it addresses inter vehicle communication usable for safety applications, i.e. crash avoidance. We choose Single Input Single Output (SISO) as the antenna scheme given its simplicity (every vehicle is only equipped with one omnidirectional antenna) and the fact this is the main antenna scheme currently considered by ETSI for VANETs research. We assume Ad-hoc communication between vehicles and therefore the presence of centralized access points is avoided. Moreover, we consider Non-Line of Sight due to vehicles (NLOSv) as the preferred type of wireless link. In NLOSv scenarios, electromagnetic waves may only be obstructed by the vehicles which are part of the network because no roadside elements are present for those scenarios.

We select GeoNetworking as the communication protocol. As described in Section 2.5, ETSI has developed GeoNetworking as the main protocol for the dissemination of messages in vehicular network. GeoNetworking offers a further classification of vehicular communications based on geographical routing: geographical unicast, topological-scoped broadcast (TSB), geographically-scoped broadcast and geographically-scoped unicast. We assume, for this thesis work, that vehicles periodically exchange CAMs and make use of one hop broadcast with no retransmissions (a sub classification of GeoNetworking’s TSB) as routing scheme as shown in Figure 3.2. Other routing schemes, as explained before, implement message forwarding which is out of the scope of this thesis work. Transmissions in a one hop broadcast scheme allows CAMs to align with their main fundamental purpose: enhance safety on vehicles by continuously informing other vehicles in the same neighborhood about their presence.

**3.1.1. Path loss model**

In this thesis work, we assume that distance-based path loss is the main propagation effect in place in accordance to ETSI DCC approach [24]. More specifically, the log-distance model is selected as the propagation model for the experiments presented later. The choice for a distance based path loss model relies on 1) the simplicity of the model, 2) the fact that in safety-related applications, the distance between vehicles plays a crucial role in assessing the urgency of information exchange in the sense that nearby vehicles have far more benefit from receiving CAMs correctly from some arbitrary vehicle than vehicles further away, and 3) the fact
that in the mobility and topology models chosen, there are few obstructions and the effects of ground-plane reflections are sufficiently modeled with a modified free-space propagation model (i.e., changing the path-loss exponent). As electromagnetic waves move across the medium, they suffer from attenuation or loss of signal strength. In other words, the signal strength (also referred as transmission power) of a frame transmitted by a given source station is usually sensed as lower upon reception by a receiving station [8]. This loss becomes higher as the distance between source and receiving stations increases. This effect is commonly known as path loss and is usually expressed in dB scale as:

$$PL(dB) = 10\log{\frac{P_t}{P_r}},$$

where $P_t$ and $P_r$ are the transmitted and received signal power, respectively [8].

Free space propagation describes the propagation mechanism of an electromagnetic wave in the (hypothetical) scenario of a transmitter and a receiver in isolation (we ignore the effects of the medium non being vacuum). Free space loss depicts the decay of the electromagnetic wave as it propagates to the receiver; it depends on separation distance, signal frequency or wavelength, parameters associated with antennas, but not on factors that are related to propagation environment. For instance, in a free space propagation model, the power received at a receiver antenna $P_r$ is given by the Friis free space equation [8]:

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

where $P_t$ is the transmitted power, $G_t$ and $G_r$ are the transmitter antenna gain and receiver antenna gain, respectively, $\lambda$ is signal wavelength in meters, $d$ is the separation distance in meters, and $L$ is the system loss factor. While the Friis free space given in Equation 3.2 provides a path loss estimate when the electromagnetic wave propagates in free space, measurements and theoretical studies have shown that in mobile radio channels, the average received power does not always follow the Friis space formula. It has been observed often that the received power still decreases with separation distance, but with a different exponent, often larger than two. This effect is captured in the log-distance model, in which the average path loss (switching to decibels as unit) for a given separation distance $d$, ($PL(d)$, in dBm, can be expressed as [8]:

$$PL(d) = PL(d_0) + 10\gamma\log{\frac{d}{d_0}},$$

where $PL(d_0)$ is the average path loss (in dBm) at a reference distance $d_0$, and $\gamma$ is the path loss exponent, which denotes the power-law relationship between the separation distance and the received power. The value of $\gamma$ is most often obtained from measured data and is usually in the range of 2–6, depending on the propagation environment. For this thesis work, we consider $\gamma = 3$.

### 3.1.2. Transmission range

The transmission power level used (at the antenna of source stations) for CAMs dissemination determines the transmission range of a given station. As shown in Figure 3.2, the transmission range of a station can be described as the maximum distance (the radius of the circumference) that a given electromagnetic wave can reach, such that the received signal strength still exceeds some threshold. The extent of the transmission range depends on the selected transmission power, i.e. higher transmission power values lead to a larger transmission range.

In accordance to ETSI DCC literature [24], we assume values for transmission power ranging from -10 dBm to 33 dBm for the stations participating in the simulated network. Intuitively, the value of 33 dBm establishes the maximum achievable transmission range which can be calculated by using Equation 3.3. In that equation, the parameter $d$ corresponds to the transmission range and can be found if the other parameters mentioned above are provided. For this thesis project we considered the parameter values shown in Table 3.1 also in accordance to ETSI DCC. $PL(d)$ is calculated based on the transmission power (33 dBm) and the CCA threshold (-85 dBm). CCA threshold helps to indicate if the channel is sensed as busy only if the instantaneous received power of a single frame is above it [32]. These calculations result in a maximum transmission range of **238.45 m** (ignoring the effects of interference and noise), assumed for the simulations in this thesis work.
### Parameters for Transmission Power Calculation

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Transmission power</td>
<td>33 dBm</td>
</tr>
<tr>
<td>CCA threshold</td>
<td>-85 dBm</td>
</tr>
<tr>
<td>Path loss exponent ($\gamma$)</td>
<td>3</td>
</tr>
<tr>
<td>Reference distance ($d_0$)</td>
<td>1 m</td>
</tr>
<tr>
<td>Average path loss ($PL(d_0)$)</td>
<td>46.7 dBm</td>
</tr>
</tbody>
</table>

Table 3.1: Parameters considered for transmission power calculation.

The transmission range of a station is further affected by phenomena like interference and noise which affect the quality of a transmitted electromagnetic wave. We consider the simulation of this behavior in the simulation environment. A better reception of an electromagnetic wave (ready for decoding) is achieved when the transmission power value is high and the levels of interference and noise are low. The reception of an electromagnetic wave under interference is characterized by the *Signal to Interference and Noise Ratio (SINR)*, the ratio between an useful electromagnetic wave and undesirable components disturbing it (noise and interference) given by Equation 3.4:

$$\text{SINR} = \frac{P_R}{\sum_i P_i^I + P_N}, \quad (3.4)$$

where $P_R$ represents the power of the received electromagnetic wave being decoded, $\sum_i P_i^I$ is the sum of the possible interfering electromagnetic waves in the target frequency and $P_N$ is the power of noise (or noise floor) coming from the environment which can be ascribed to the environmental thermal noise with an average power $N_t = kT_0B$, where $k$ is Boltzmann’s constant ($1.38 \times 10^{-23} \text{J/K}$), $T_0$ is the temperature and $B$ is the bandwidth [8]. At 290 K, $kT_0B$ is -114 dBm/MHz; with a 10 MHz channel, a noise floor of -104 dBm is found; it is typically set in the range (-104, -99) dBm. SINR is indeed a significant parameter directly linked to the probability of correctly receiving a frame. SINR expresses that the stronger the signal, the better the signal quality and hence the lower the packet loss probability. The same consideration is valid for the interference, i.e. the weaker the interference, the better the signal quality.

Specifically for vehicular environments, ETSI states that for the correct reception of messages a SINR threshold must meet according to Equation 3.5 [24]:

$$\text{requiredSINR}(\text{datarate}) = \min \text{SINR} + \text{backoffSINR}(\text{datarate}), \quad (3.5)$$

where $\text{requiredSINR}(\text{datarate})$ refers to the required SINR for a given datarate, $\min \text{SINR}$ is the expected SINR at which other ITS stations can successfully decode messages and equals 10 dBm [24]. $\text{backoffSINR}(\text{datarate})$ is given by Table 3.2. For this thesis work we consider 6 Mbps as default datarate.

<table>
<thead>
<tr>
<th>Datarate (Mbps)</th>
<th>backoffSINR (dBm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>3</td>
<td>0</td>
</tr>
<tr>
<td>4.5</td>
<td>1</td>
</tr>
<tr>
<td>6</td>
<td>3</td>
</tr>
<tr>
<td>9</td>
<td>5</td>
</tr>
<tr>
<td>12</td>
<td>8</td>
</tr>
<tr>
<td>18</td>
<td>12</td>
</tr>
<tr>
<td>24</td>
<td>16</td>
</tr>
<tr>
<td>27</td>
<td>17</td>
</tr>
</tbody>
</table>

Table 3.2: SNR backoff values.

Figure 3.3 shows an example on how the effective range of the transmitter is reduced by a concurrent transmission of an interfering hidden station. The full radio range is a circular area shown as dashed line, where the radius of this circle is given by the noise limit when the interferer is not transmitting. It is important to understand that the transmission range is reduced in all directions and only receiving stations located
3.2. Transmit Power Control (TPC)

In this section we explain the assumptions we make regarding power control for the transmission of CAMs in our scenarios. We state that the transmission range of any station depends on the transmit power applied by any station even though it is also affected by interference. For this thesis project we consider transmit power values ranging between -10 dBm and 33 dBm (standardized by ETSI DCC) for evaluation and comparison purposes of the proposed and existing algorithms for channel load control.

We assume that the stations in our simulation scenarios utilize TPC (manipulation of transmit power) to adjust their effective transmission range. However, the adjustment of the transmit power not only influences the transmission range but also the channel load and the connectivity of the network itself. Stations utilizing low transmit power values certainly reduce their transmission range and consequently their neighborhood (reachable stations). As a result, less contention for channel access (lower channel congestion) takes place. The drawback comes at the price of less stations listening to potentially important CAMs because the transmission range reduction might lead to the isolation of the stations utilizing too-low transmit power values. Intuitively, the use higher transmission power values causes larger transmission ranges but also causes higher channel load values as a consequence of increased channel access contention and collisions.

3.3. Emulation of CAMs

In this section we present the assumptions that we made regarding the emulation of CAMs. As it was earlier stated, these messages represent the basic data structures to support communications among vehicles in VANETs. Figure 3.4 shows the basic structure of a CAM with field sizes indicated in bytes [56]. The purpose and contents of each CAM field are described as follows:

- **Header.** Consists of protocol version, IDs of message and vehicle.
- **Basic container.** Consists of position of the object received from a *global navigation satellite system (GNSS)* such as *global positioning system (GPS)*, what kind of object (passenger car, motorcyclist, bus,
3. ITS MODELING AND SIMULATION CONSIDERATIONS

- **Basic vehicle container HF**: This field is included in every CAM (high message frequency, HF) and it contains information about heading, speed, curvature, driving direction (backward or forward), and the role of the vehicle if applicable (e.g., public transport, special transport, dangerous goods, road work).

- **Basic vehicle container LF**: This field is not included in every CAM (low frequency, LF) and it contains more static data about the vehicle itself such as size, status of exterior lights, and path history. The path history is made up of a number of path history points, which can be at maximum 23 points. Every point is approx. 8 bytes and contains the position at a specific point in time.

- **Special container**: This field is included if the role of the vehicle contained in the basic vehicle container HF has indicated if it is public transport, dangerous goods etc., and then additional bytes (1-4 bytes depending on role) are included to describe the vehicle more precisely.

<table>
<thead>
<tr>
<th>Header</th>
<th>Basic container</th>
<th>Basic Vehicle container HF</th>
<th>Basic Vehicle container LF</th>
<th>Special container</th>
</tr>
</thead>
<tbody>
<tr>
<td>6</td>
<td>18</td>
<td>14</td>
<td>max 176</td>
<td>1-4</td>
</tr>
</tbody>
</table>

Figure 3.4: CAM structure [56].

For the transmission of a CAM, this must be encapsulated in a packet consisting of the CAM data and headers and trails from other communication layers. Figure 3.5 shows the fields of a generic CAM packet with sizes indicated in bytes [56]. The PHY, MAC, LLC, SNAP, BTP and GeoNetworking (GN) headers together with the MAC trail are fixed in size. The CAM data will be 14 bytes when only the high frequency (HF) part is transmitted and when the low frequency (LF) part is present containing the path history the CAM will typically be 90 byte assuming 10 points of path history. The PHY trail, which consists of the tail bits and the pad bits to reach an even multiple of coded bits per OFDM symbol, is at least 6 bits when only tail bits are present and up to 293 bits assuming the highest transfer rates with 288 bits per OFDM symbol.

<table>
<thead>
<tr>
<th>PHY header</th>
<th>MAC header</th>
<th>LLC header</th>
<th>SNAP header</th>
<th>BTP header</th>
<th>GN header</th>
<th>CAM data</th>
<th>MAC trail</th>
<th>PHY trail</th>
</tr>
</thead>
<tbody>
<tr>
<td>5</td>
<td>32</td>
<td>3</td>
<td>5</td>
<td>4</td>
<td>36</td>
<td>14(HF)/90(LF)</td>
<td>4</td>
<td>&gt;1</td>
</tr>
</tbody>
</table>

Figure 3.5: Generic CAM packet [56].

From Figure 3.5 we observe that CAMs have usually a size of around 200 bytes. Therefore in this thesis work we consider 200 bytes as the minimum size of CAMs. We also consider CAMs with size 500 and 1000 bytes for our experiments. The benefits, at application for example, rely on the fact that more (safety) information can be shared among vehicles possibly at lower message frequencies. However CAMs sizes also imply higher channel load values due to higher transmissions delays and collisions. Regarding the transmission inter message times (time between subsequent messages) we select a range between 0.04 and 0.1 seconds in accordance with ETSI DCC [24].

Another important assumption we make concerns the emulation of CAMs given the limitations of the selected simulation tool. The simulation tool, presented in Section 3.4, does not offer native implementation and support of CAM messages despite its IEEE 801.11p support. To counter this, we emulate CAM transmissions (normally taking place over the GeoNetworking and BTP protocols) by broadcasting suitably sized messages in a UDP/IPv4 datagram. In order to approximate to the desired transmission scheme, we disable routing and forwarding in IPv4. Given the difference in overhead of BTP/GN and UDP/IPv4, we choose to use UDP/IPv4 broadcasts (with no acknowledgement scheme) as they closely resemble CAM broadcasts in VANETs.
3.4. Dissemination of CAMs

For each station transmitting CAMs in the simulation environment we assume transmissions in a one-hop broadcast scheme as it was mentioned earlier in this chapter. In that scheme CAMs are only received by listening stations within the transmission range of transmitting stations provided that the SINR of 3 dB is achieved for the successful reception of CAMs. For VANETs, no retransmissions take place in a one-hop broadcast scheme. As explained earlier, interference can adversely affect the effective transmission range of stations. Even though in this thesis work we do not aim to directly alleviate the effects of interference this is achieved indirectly by the manipulation of TX power values. Therefore CAMs transmissions suffer from this effect.

In order to calculate the transmission time of CAMs considered for our simulations, and in accordance to ETSI [24], we assume an inter message time of 0.1 seconds (i.e. 10 messages per second) and a fixed transmission speed (data rate) of 6 Mbps. As it will be later explained, ETSI only considers the adaptation of transmission power and inter message time values for CAMs transmissions. As IPv4 is assumed for the transmission of CAMs then the overhead added by MAC, IPv4 and UDP is also considered as 64 extra bytes. With those parameters in mind, the transmission time of every CAM from source to destination can be theoretically calculated as shown in Equation 3.6.

\[
\text{CAM Time} = ((\text{payload} + \text{overhead}) \times 8)/(6 \times 1024 \times 1024) = (1064 \times 8)/(6 \times 1024 \times 1024) = 1.353 \text{ms} \quad (3.6)
\]

Moreover, for our simulations each station selects a random initial time taken from a uniform distribution before transmitting its first CAM. This is done to model the asynchronous nature of the different vehicles’ CAM transmission times. Subsequent CAMs are then sent based on the selected inter message time depending on the chosen DCC mechanism. In general, only ETSI DCC mechanism utilizes an adaptive inter-message times as it employs TRC as part of the strategy for congestion control.

3.5. Mobility scenarios

As it was stated in Section 3.1, we consider static and mobile vehicles scenarios in this thesis work with the purpose of showing the effectiveness of the existing and proposed algorithms under the influence of mobility. We first classify the scenarios based upon two aspects: 1) the mobility of the vehicles and 2) the randomness of the inter-vehicle distances. Subsequently, we discuss in more detail the vehicle mobility model used.

3.5.1. Static traffic scenarios

**HOMOGENEOUS AND STATIC INTER-VEHICLE DISTANCES:**
Vehicle positions are static, i.e. the vehicles do not move during simulation time. All vehicles have the same inter-vehicle distance with their front and rear neighbors. This distance is a parameter of the model.

**HETEROGENEOUS AND STATIC INTER-VEHICLE DISTANCES:**
Vehicle positions are static, i.e. the vehicles do not move during simulation time. Inter-vehicle distances of all vehicles with respect to their front and rear neighbors is randomized (different) from uniform distribution before simulation start. These distances are fixed and do not change during simulation time.

3.5.2. Mobile traffic scenarios

**HOMOGENEOUS AND STATIC INTER-VEHICLE DISTANCES:**
Vehicles move from West to East. All vehicles have identical, constant, inter-vehicle distance with their front and rear neighbors, despite the movement of vehicles. This means that all vehicles move as a single entity.

**HETEROGENEOUS AND DYNAMICALLY CHANGING INTER-VEHICLE DISTANCES:**
Vehicles move from West to East. Inter-vehicle distances vary with time (i.e. vehicles stay close but they are individually free to accelerate, decelerate and brake) and with space (i.e., they are generally different for different pairs of successive vehicles).
3.5.3. IDM car following model

Subsequent sections in this chapter present the simulation tools considered in this report. First, in this section we describe the Intelligent Driver Model (IDM) model that we use for the dynamic inter-vehicle distances. In traffic flow modeling, the IDM developed by Tiebert et al. [61] is a time-continuous car-following model for the simulation of freeway and urban traffic. It was developed in the year 2000 to improve upon results provided with other "intelligent" driver models, which presented less realistic properties. IDM is a reference model, widely implemented and used for vehicular traffic research [13]. Moreover vehicular traffic simulators as Simulation of Urban Mobility (SUMO) implement IDM as car following model [36]. We consider SUMO for this thesis project as explained in later sections.

IDM characterizes the behavior of drivers depending on the front vehicle. The instantaneous acceleration of a vehicle is calculated by the following equations:

\[
\frac{dv}{dt} = a \left[ 1 - \frac{v^4}{v_0^4} - \frac{s^2}{s^*_0} \right]
\]

(3.7)

where \(v\) the current speed of the vehicle, \(v_0\) is the desired velocity, \(s\) is the distance from preceding vehicle, and \(s^*_0\) is the so-called desired dynamical distance which is calculated as a function of the minimum bumper-to-bumper distance \(s_0\) as follows:

\[
s^*_0 = s_0 + vT + \frac{v\Delta v}{2\sqrt{ab}}
\]

(3.8)

where \(T\) is the minimum safe time headway (the carefulness of the driver), \(\Delta v\) is the speed difference with respect to the front vehicle and \(a\) and \(b\) are acceleration and deceleration values. In general, as shown in Table 3.3 typical values for the parameters of the IDM are usually considered.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Typical value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Desired velocity ((v_0))</td>
<td>120 km/h</td>
</tr>
<tr>
<td>Minimum safe time headway ((T))</td>
<td>1.0 seconds</td>
</tr>
<tr>
<td>Minimum bumper-to-bumper distance ((s_0))</td>
<td>2 m</td>
</tr>
<tr>
<td>Acceleration ((a))</td>
<td>1.0 m/s²</td>
</tr>
<tr>
<td>Deceleration ((b))</td>
<td>1.5 m/s²</td>
</tr>
</tbody>
</table>

Table 3.3: Typical values for IDM parameters.

When combined, these formulas give the instantaneous acceleration of the car, divided into a “desired” acceleration on a free road, and braking decelerations induced by the preceding vehicle. By smoothly varying the instantaneous acceleration, the IDM can realistically mimic car-to-car interactions on a single-lane and straight road. \(s^*_0\) corresponds to the gap when following other vehicles in steadily flowing traffic. In addition, \(s^*_0\) increases dynamically when approaching slower vehicles and decreases when the front vehicle is faster. Interesting real world situations, such as queuing of vehicles behind a slow car, or speed reduction in presence of congested traffic can be reproduced.

3.6. Simulation tools

This section describes the software tools used for our simulations to be presented in Chapter 5.

3.6.1. NS-3 simulator

For the simulation of vehicular networks, a great variety of software tools have been developed. The selection of a certain simulation tool depends on the networking features to be tested and the required level of detail. Other factors have to do with portability, programming languages and computer hardware requirements and even the costs of the tool itself.

We select Network simulator (ns-3) as simulation tool for this thesis project mainly due to its open source availability, its low computational requirements and its development and online support features [49]. Open
3.6. Simulation tools

Source ns-3, successor of the popular ns-2, is a discrete-event network simulator which offers scalability, flexibility, clean design and real-world integration. For development, this simulation tool offers C++ and Python as programming languages. Additionally, it supports standard APIs like Berkeley sockets and POSIX threads.

Even though ns-3 was introduced in 2006, there are still ongoing activities for porting ns-2 features into ns-3. Therefore, there are still several models not available in ns-3. A GUI for graphically building topologies is still in experimental phase. Despite its drawbacks, ns-3 is widely used by the community of computer networks researchers and is considered to have high overall performance in comparison with other tools as demonstrated by Weingartner et al. [65].

Figure 3.6 shows a diagram of the overall software organization in ns-3. From it the basic interacting structures and models can be depicted. "Helpers" data structures are of particular interest because they provide easy-to-use templates to create simple and more advanced network elements like channels, stations, interfaces and applications. From Figure 3.6 we can observe the relationship of the network stacks implemented by ns-3 and their functionality which is condensed by the so-called helpers which are available for easy use by new developers. Figure 3.6 shows that ns-3 shortcuts the development process by predefining higher network structures which are available for adjustment by the development needs. Therefore, developers only need to configure parameters related to nodes, networks, mobility and tracing instead of developing from scratch.

![Figure 3.6: Software organization in ns-3 [49.]

3.6.2. SUMO traffic simulator

With the purpose of adding realism to the simulation of wireless networks, we consider a traffic simulator called SUMO as useful in combination with ns-3 [36]. SUMO is an open source, highly portable, microscopic and continuous road traffic simulation package designed to handle large road networks [36]. SUMO has been developed mainly by the Institute of Transportation Systems at the German Aerospace Center together with external parties that supported different extensions to the simulation suite. Krajzewicz et al. [41] have largely contributed to the development of SUMO. Figure 3.7 shows the general procedure followed in SUMO to generate traffic networks information. This process starts by defining the basic parameters for topology, stations and traffic models (input files). The next step is to execute commands to generate SUMO files (netconvert and netgenerate). Finally, additional SUMO commands are applied to export usable SUMO files in other formats (networks). SUMO is compatible with ns-3. Output files from SUMO can be converted to ns-3 readable versions (.tcl files format) which can be imported by that network simulator.

SUMO is a powerful and manageable tool and was therefore selected for this thesis project. SUMO allows the building of customized road networks with any topology desired. The microscopic feature allows the setup of different kind of vehicles with individual characteristics such as size, speed, acceleration, deceleration, heading direction, etc. Car speed in particular can be computed via the available car-following models in SUMO [41]: Krauss model, intelligent driver model (IDM), Kenner’s three phase model and the Wiedemann...
model. In particular for this thesis work, we select IDM for simulation scenarios that require mobility.

3.6.3. Simulation tools integration

In order to simulate mobile vehicular traffic we integrate features of ns-3 and traffic simulator SUMO. As indicated in Figure 3.8, the process for the addition of mobility to the vehicles in the scenario began with the creation of the network topology. Then we take subsequent steps until the generation of an output text file (in .TCL format) containing the individual data of mobility for the total number of stations and the entire simulation time in SUMO. The final steps are taken in ns-3 to import the mobility data and to aggregate mobility within the network scenario.

The main purpose of that coupling is to investigate the performance of the baseline and proposed algorithms presented in this thesis work under a realistic scenario: vehicles moving through the highway topology with variations in their speed and inter-vehicle distance.
4

DESCRIPTION OF EXISTING AND PROPOSED DCC MECHANISMS

This chapter presents the mechanisms considered in this thesis for channel load control in VANETs. The chapter aims to introduce the mechanisms from a functional point of view and leaves their assessment and comparison for Chapter 5. In Section 4.1 we refer again to the channel load concept. In Section 4.2 we describe the base line mechanisms and in Section 4.3 we describe our proposed mechanisms which are based on control theory.

4.1. Channel load concept

Channel congestion, as mentioned in Section 2.6, can be defined as the perception of the medium’s status (e.g. IDLE, BUSY) in a given period of time and sensed by any station present in a given network. It can be measured in terms of channel load and behave according to the number of intended transmissions. High channel load values have a negative impact on network metrics like end to end delay, throughput, packet loss, ratio of transmitted/received packets, etc. For C-ITS, the packets are referred to CAMs and DENMs.

Channel load measurement plays a key role for this thesis work and is extensively mentioned in the following sections. The mechanisms to be explained in the following sections utilize channel load as metric to determine if a communication channel is occupied. ETSI has defined the procedure for channel load measurement [24] which we consider as base for our research work. This procedure is carefully explained in Chapter 5.

4.2. Base line mechanisms

We consider two base line mechanisms in this thesis for comparison with our proposed mechanisms. We describe the mechanisms employed (if any) by both base line mechanisms in their attempts to maintain sufficient network performance under high channel load conditions.

4.2.1. Simple IEEE 802.11p

Our first base line mechanism is to use “plain” IEEE 802.11p, as explained in Chapter 2, for sending and receiving messages, without provisions for controlling the channel load. As we have stated before, IEEE 802.11p provides the rules for encapsulation and de-encapsulation of frames at different layers to allow successful transmissions from source to destination vehicles.

The simple version of IEEE 802.11p does not feature a mechanism to observe and reduce high channel load values. Therefore, fixed values for TX power (33 dBm) and inter message time (0.1 seconds) are used for this basic mechanism. More specifically, at layer 2, IEEE 802.11p focuses on achieving fair medium access for every vehicle in the network by executing mechanisms like EDCA as it was explained in Section 2.1.6.4. For vehicles communicating under IEEE 802.11p, the measured channel load reaches higher values as the number of vehicles in the network increases. This means that the network performance decays as the number
of vehicles utilizing the same communication channel increases because no relief strategy is implemented.

### 4.2.2. ETSI Decentralized Congestion Control

Our second base line mechanism is ETSI Decentralized Congestion Control. From the modules of the DCC access layer, which is part of that mechanism, a control loop stands out as the core element which optionally utilizes TPC, TRC, TDC and TAC for channel load control [24]. The feature of decentralization of ETSI DCC refers to the fact that each vehicle in the network individually evaluates its own channel load level and implements the necessary steps based on the control loop strategy. The access layer control loop is fed by measured channel load values, obtained by channel probing mechanisms. The operation of the control loop relies on a 3-state machine shown in Figure 4.1 with the following state options: relaxed, active and restrictive. Switching to a certain state depends on the continuously measured channel load value and the thresholds set for entering that state. For this channel load strategy ETSI has defined the use only of TPC and TRC. Depending on the current state, certain transmission power values and inter messages time limits are set to predefined values [24].

Throughout this thesis, we express channel load values in terms of ratios between zero and unity (both inclusive). ETSI clearly describes the steps and considerations employed for the calculation of channel load. For this thesis work, channel load is considered the key metric to analyze. A detailed explanation of the calculation of channel load is presented in Chapter 5.

In this section we describe the operation of the control loop. Figure 4.1 shows the structure of the ETSI DCC state machine, the parameters considered for every state and the conditions required to switch between states. In this figure, CL refers to channel load and TX power to transmission power. The rules for switching from one state to another can be explained as follows: Initially, every station (vehicle) in the network enters “relaxed” state with the corresponding parameters (TX power of 33 dBm and inter-message time of 0.04 seconds). If the channel load value is measured and remains above the upper threshold (CL_up1 = 0.2) for a minimum period of 1 second then a state switch (from “relaxed”) to “active” state occurs in which 15 dBm is used as TX power and 0.5 seconds is used as inter-message time. From the “active” state, two transitions are possible: 1) if a higher channel load value is detected and is maintained above the upper threshold (CL_up2 = 0.5) for a minimum period of 1 second then a transition (from “active”) to “restrictive” occurs and, 2) if a lower channel load value is measured and is maintained below the bottom threshold (CL_down1 = 0.15) for a period of 5 seconds then a state transition to “relaxed” occurs. In “restrictive” TX power is set to -10 dBm while inter-message time is set to 1 second. Finally, if the “restrictive” state is reached, a transition back to “active” occurs if the channel load value is detected and maintained below the bottom threshold (CL_down2 = 0.4) for at least 5 seconds. Hence at higher loads, both the TX power and the inter-message time are reduced to decrease the channel load, with a more aggressive such reduction as channel loads are higher.

It is important to notice that switching from one state to another requires certain channel load value to be detected at least for a 1 second or 5 seconds window as explained above. Switching to less restrictive states (from “restrictive” to “active” or from “active” to “relaxed”) requires a longer period of maintained channel load (5 seconds) than switching in reverse direction (1 second). This means that the ETSI DCC control loop operates with a conservative strategy when channel load increases and therefore a switch occur (within 1 second) to states in which smaller values for TX power (reducing the stations TX range) and larger values for inter-message time (sending CAMs less frequently. On the other hand, reaching states where larger TX power values and smaller inter-message times requires that channel load is below certain threshold for a longer time (5 seconds).

These switching conditions are strict: every value within the 1 second or 5 seconds windows must satisfy the conditions in order to be considered for switching purposes. The period for channel load calculation is usually set to 1 second.

ETSI DCC strategy works in the sense of bounding channel load values. However its main drawback is inherent instability due to state oscillations [44]. In other words, with ETSI DCC, the channel load does not converge to a constant (operational) value. As depicted in Figure 4.2 introduced by Werner et al. [66], state switching (indicated in the right axis) mainly between “relaxed” (0) and “active” (1) leads to high instantaneous channel load values for the former and low instantaneous channel load values for the latter (as in-
4.3. Proposed mechanisms

Along with the quantitative assessment presented in Chapter 5, the following section represents the core of this thesis work as it presents the main contributions to VANETs performance optimization. The mechanisms described in this section aim to improve the performance of IEEE 802.11p and ETSI DCC by proposing the use of basic control theory features in order to control channel load. The main idea is to control the channel load to an operational (“target”) value in a continuous manner, as opposed to the approach of a “discretized” control loop used in ETSI DCC. Our intuition is that aiming for a target channel load value allows for an optimized usage of the communication channel avoiding oscillations produced by ETSI DCC. However finding a
suitable target for channel load is not a straightforward task and is also dependent on the scenario and network parameters [58]. Both mechanisms presented here use variable transmission power (TX power) while maintaining the inter message times as constant. In other words, transmission power control (TPC) is the only considered strategy for these mechanisms. In contrast, ETSI DCC uses both TPC and TRC.

4.3.1. Basic process control theory

Control theory is a branch of engineering and mathematics which aims to stabilize a given system (often called process or plant). Control theory defines different kind of strategies, one of them is called **closed loop control** in which feedback from measurements at the output of the system is used to correct in some way the behavior of the system. Nowadays, control theory is highly specialized and effective in different technical industries, such as electronics, climate modeling, chemical, petrochemical and manufacturing.

**CLOSED LOOP CONTROL**

Figure 4.3 shows the fundamental structure of a closed loop control. As shown in this figure, a target system's variable (system output variable) is continuously monitored via a sensor block. The value of the measured system output variable is compared to a reference value. The reference value is typically fixed and represents the desired value that the control loop aims to reach for the target system. The comparison between the measured and reference values produces an error value which is the difference between the current and the desired value for the system output variable. The error calculated becomes the input of a controller block, explained later, which reacts depending on the error value and calculates the compensation to be applied on a second variable (system input variable). The manipulation of the system input variable has a direct impact on the system behavior and consequently on the system output variable.

The main purpose of a closed loop control is to reach the desired system output variable value (reference value) by continuously steering the system input variable. Another key purpose is the achievement of steady state systems, i.e. not oscillating systems.

In order to understand the operation of closed loop controls a typical example can be used: room temperature control in air conditioning systems. The aim of those systems is to maintain certain room temperature (reference value) by utilizing a temperature sensor to measure the current temperature (system output variable) and to translate it from an analog to a digital signal. The error value is then calculated and it represents the difference between measured and the desired room temperature. A controller unit (electronically implemented) takes care of reading the error signal and produce the corresponding compensation that will modify the room temperature (system). In the case of air conditioning systems the switch on or switch off of an integrated air compressor unit (system input variable) determines also the temperature of the air that is ventilated into the room. The controller unit is also in charge of continuously sensing the room temperature to maintain it as close as possible to the desired set value (steady state).

![Figure 4.3: Basic closed loop control structure.](image)

**PID CONTROLLERS**

Different types of controllers exist, however the proportional-integral-derivative (PID) controllers are the most widely used. Equation 4.1 shows the general form of a classical PID controller.

\[
u(t) = K_p e(t) + K_i \int e(t) dt + K_D \frac{d}{dt} e(t),\]  

\( (4.1) \)
where $u(t)$ is the system input (as a function of time $t$) that feeds the system, $e(t)$ is the measured error and $K_p$, $K_i$ and $K_D$ are tunable parameters that increase or reduce the effects of the proportional, integral and derivative terms in the equation, respectively. Each term in the equation has a specific target:

- The proportional term provides an overall control action proportional to the error signal. The proportional term applies immediate correction as fast as possible to reach the desired reference value i.e. if the error value is large then the compensation will be large too. However its drastic compensation mechanism usually has drawbacks like surpassing the desired value which is known as overshoot.

- The integral term: reducing steady state errors through low frequency compensation by an integrator. The effects of this term is more conservative as it keeps track of the last measured error values. Based on the progress detected towards reaching the desired reference value, the integral term will lead to add larger compensation values if not enough progress has been achieved. If sufficient progress has been achieved, then the compensation is smaller which leads to decrease overshooting effects.

- The derivative term: improving transient response through high frequency compensation by a differentiator. The derivative term predicts the behavior of the system and therefore adds settling time and stability. The derivative term aims to slow down the system changes towards the desired reference value.

In practice the derivative term is usually omitted from the controller block, as it is highly affected by signal noise in the system. Moreover, the overshoot that the derivative term aims to minimize can be controlled by correctly tuning the proportional and integral terms. As a conclusion, PI controllers are mostly used nowadays. Figure 4.4 and Figure 4.5 show the effects of proportional and integral terms on the performance of PI controllers. Both figures aim to explain the behavior of a certain measured signal (which can be of any type) under the control of a PI controller. Therefore the y axis has been suppressed while the x axis does not have units but represents time. Figure 4.4 shows the desired set point (green line) and the system response under two different values for $K_p$ ($K_i$ is assumed as constant). In this case, a high value of $K_p$ (red line) produces a rapid response towards the set point but also produces a higher overshoot and a system with more oscillations. A lower value of $K_p$ (blue line) gives a system with a slower response but also with less oscillations.

![Figure 4.4: Effects of $K_p$ values on PI controllers.](image)

Figure 4.5 shows the desired set point (green line) and the system response under three different values for $K_i$ ($K_p$ is assumed as constant). As depicted in this figure, a high value set for the integral factor (red line) indeed helps to eliminate the oscillations produced by the $K_p$ factor. However the overshoot effect is evident. Applying medium values for $K_i$ (blue line) decreases oscillations and overshoot. A lower value for $K_i$ (purple line) should eliminate overshoot and oscillations and should make the system reach its set point in a smoother way. A PI(D) is always a compromise between transient (fast) response with overshoots, and a gradual (slow) response with no or very few overshoots. The exact dimensioning of a PI(D) therefore largely depends on the desired behavior and on the specifics of the considered system/environment.
CONTROL LOOP TUNING
Each system manipulated under PI controllers’ mechanisms is indeed different. Therefore unique set points values, input and output system variables, and proportional-integral factors need to be carefully determined. PI factors in particular require special attention in order to find the optimal values to make the system more stable. The mechanisms employed for this tasks are commonly known as loop tuning and can be achieved heuristically or more formally.

Heuristic loop tuning is employed when the system can be observed and analyzed offline until optimal parameters can be found. Manual tuning method relies on a combination of methods that keep one of the parameters as constant (fixed) while other is variable. Ziegler-Nichols method [68] proposes to first set both factors to zero and then increase one of the factors gradually until detecting oscillations. Once this scenario is found, other conditions are applied where PI parameters are increased or decreased based on predefined factors.

Formal loop tuning is employed at large industry scale by using complex PI tuning software. This method involves the use of online data gathering and process model to produce optimal values. In both cases, control loop tuning is not an easy task and continues to be a subject of research nowadays.

Despite their differences in complexity, both mechanisms are considered as static and scenario-dependent because the PI factors found are only applicable for the analyzed system conditions. This means that for a different scenario the PI factors have to be recalculated. For this thesis work we use the heuristic mechanism for PI loop tuning therefore we choose to execute several simulation tests to find the optimal parameters as we show in Chapter 5.

4.3.2. Transmission power control with simple PI control loop
The first algorithm proposed in this thesis work is inspired by the control theory concepts that have been already introduced. The elementary idea is to enhance the performance of the ETSI DCC control loop at the access layer by implementing a PI controller in every vehicle of the network. The main purpose of this PI control loop is to stabilize the load on the communication channel and avoid oscillations while aiming to reach a desired set point (in this case, of the channel load CL). We consider that by selecting a PI control loop and by aiming to stabilize channel load can lead to better performance than the control loop offered by ETSI DCC. As we have founded our assumptions on the largely studied field of control theory it is our expectation that a correct implementation of the PI control loop and its parameters will lead to the stabilization of channel load. However we expect that the effects of factors like mobility will have an impact on the performance results as they will add variability to the system.

In accordance to the theory introduced in the previous section, the PI controller we propose in this report has the following characteristics which are based on the basic structure of a closed control loop (Figure 4.3).
4.3. PROPOSED MECHANISMS

A given vehicular network acts like the target system whose loading is desired to be stabilized. We measure channel load via the mechanisms to be described in Chapter 5. It represents the system output variable which is the final target for control. We also propose a reference channel load as the desired set point. Our implemented PI controller assesses the amount of error in channel load and aims to compensate it by manipulating the transmission power value (TX power) used by each vehicle for CAMs transmissions. Therefore TX power is considered as the input system variable or the knob that modifies the system behavior and consequently the channel load value. It is important to state that once the reference channel load value has been reached the PI controller will try to maintain it by adjusting the TX power value based on the feedback mechanisms. This means that the reference channel load value is a fixed value and therefore has to be determined during the design and tuning of the PI controller.

As it was also stated before, PI controllers offer benefits towards the stabilization of a given system. However, an efficient loop tuning based on the manipulation of the proportional ($K_P$) and integral ($K_I$) factors is a challenging task. The optimal values of $K_P$ and $K_I$ are too sensitive to other system parameters like the number of vehicles in range. In other words, using only the channel load as ‘observable input’ to the controller does not give a satisfactory optimization of the control loop and therefore more information is needed. A control loop with as small as possible number of input parameters is highly desirable. Unfortunately, using channel alone is not good enough.

It is important to state that, for this algorithm, we consider the reference channel load value and the proportional-integral factors as fixed. This means that the parameters we have found (via control loop tuning as explained in Section 4.3.1.3) for the characteristics of our PI controller and the select network scenarios are specifically chosen to work in those scenarios, i.e. this is not a unique solution for the universal control of VANETs. This assumption is also in accordance to control theory which states that every target system must be treated individually and the tuning of the PI controller has to be tailor made. Intuitively, the existence of a self-optimisation layer above the TPC layer would be useful for an automatic tuning process of the PI control loop.

Figure 4.6 shows the basic structure proposed for the closed loop control. A closer look into the control block shows that it depends on the proportional and integral factors which are obtained by the tuning process that was explained above. The output the control block determines the TX power of a given vehicle, i.e. the TX power that vehicle must use in order to achieve a desired channel load value. This figure also shows the relationship between TX power and channel load which is the core of this thesis project, i.e. channel load control based on TPC.

![Figure 4.6: Simple PI control loop.](image)

As shown in Figure 4.6 the parameters of the simple PI control loop are the proportional $K_P$ factor, integral $K_I$ factor and the reference channel load $sp$. The latter is compared to the measured channel load which is periodically calculated to determine the error value $e(t)$. Finally, the TX power value runs from the lowest and highest limits determined by ETSI as it is explained in Chapter 5.
4.3.3. TX power control with a simple PI control loop and channel load share information

The motivation for the second algorithm comes from the idea of considering additional information for the simple PI control approach to optimize its performance. The idea is to provide the controller block with additional information from a given vehicle’s neighborhood to modify the proportional and derivative factors in a dynamic scheme. We propose the addition of the so-called channel load share (CLS), a dynamic and multiplicative factor to be included in the proportional and integral blocks of Figure 4.6 which is defined by Equation 4.2.

\[
CLS = \frac{CL}{neighbors + 1},
\]  

where \( CL \) refers to the measured channel load and \( neighbors \) refers to the number of neighbors sensed by each vehicle.

In a vehicular network, the controller implemented in every vehicle utilizing the first approach with a simple PI control loop will try to stabilize the channel load based only on the measured channel load. Therefore it will react according to the previously tuned \( K_P \) and \( K_I \) parameters and will make use of values of TX power either too high or too low in pursuit of the channel load stabilization. Too high values might lead to overshoots while too low values might lead to a system converging slowly. Moreover, these drastic changes in TX power might also impact other secondary performance metrics relying on the transmission range like the number of successfully received messages. By utilizing the second approach, the PI controller utilized by the vehicles will initially have the same response as the first approach if the same \( K_P \) and \( K_I \) factors are used but will have a smoother reaction towards the stabilization of the channel load as shown in Figure 4.8. The reason behind this relies on the fact that the CLS factor directly impacts the sensitivity of the \( K_P \) and \( K_I \) factors and reduces or augments their effect on the system based on the level of responsibility (share) of the target vehicle. Our expectation is that the second approach will have a smoother response and the TX power values will not have drastic changes.

In order to keep track of the neighbor vehicles, a neighbor-discovery mechanism (as mentioned above) must be employed by each vehicle. This mechanism is based on the implementation and update of a so-called location table. Every time a CAM (or, in fact, any message) is received by a given vehicle, the ID of the source vehicle is decoded by the receiving vehicle. (Note that we can typically obtain the source-vehicle ID by inspecting its MAC header; there is no need to actually inspect the CAM messages themselves.) Then a new record is inserted into the location table and contains basically the ID of the source vehicle and a time stamp of the last message received. This means that only one entry for each neighbor vehicle must be present in the location table and must correspond to the last message received. These data structures make use of time-to-live thresholds to determine whether a certain vehicle is considered as neighbor at any given time. Vehicles surpassing those thresholds are removed from the location tables and are no longer considered as neighbors until new messages are received from them in the future. The use of time-to-live thresholds (usually 250 µs) is important as it directly influences the channel load share that a given vehicle measures.

As it is for the simple PI control loop each vehicle in a given network has only limited responsibility on fixing the error in the measured channel load; the “complete” responsibility is to be shared among all vehicles present in the short range neighborhood. Adding the channel load share information gives our second approach the feature of explicitly exploiting knowledge regarding the contribution of a given vehicle to the overall measured channel load. Figure 4.7 aims to graphically explain the concept of CLS from our perspective. In this figure, which corresponds to a certain point in time, five vehicles stand on an open road at different distances from each other with their TX ranges represented by a dotted blue circumference assuming equal TX power values. For all vehicles CLS value is indicated as the proportion of channel load divided by the number of neighbors. This ratio of responsibility is named channel load share in this thesis work. In this example, vehicles 1 and 5 do not sense neighbors and therefore they determine that they are fully responsible for the measured channel load. In the case of vehicles 2 and 4, both sense one neighbor (vehicle 3) and therefore their CLS (CL/2) is lower than it is for vehicles 1 and 5. Vehicle 3 is highlighted as the vehicle with the lowest CLS (CL/3) because it senses two neighbors (vehicles 2 and 4).

Once the channel load share has been determined by a given vehicle, this information is utilized to mod-
ify the PI control block operation. The idea is to utilize the channel load share value as a factor which dynamically modifies the proportional and integral parameters of the controller block. The reason behind this process is the assumption that the controller block will react more accordingly to the vehicle's responsibility on the measured channel load. In other words if the vehicle has less responsibility then its controller block must take less aggressive actions towards channel load relief which translates to smaller changes of TX power. Based on this assumption, it is expected that vehicles with more responsibility adopt more aggressive actions. For this algorithm it is expected that the network performance improves the results obtained by the simple PI control loop approach.

Note that, in view of earlier remarks, a neighborhood discovery mechanism does not require the specific periodic broadcast of CAM messages. In fact, any periodic message will do, and for instance in ETSI GeoNetworking, so-called GeoNetworking beacons are sent in case the transmitter has been idle for a certain period of time, precisely to the purpose of neighbor discovery and Location-Table maintenance [23][8]. In other words, neighborhood discovery is already present in GeoNetworking, and no modifications (other than building a Location Table at layer 2) are required.

Figure 4.8 shows the structure of the PI control loop with channel load share information. As explained before, it has the same structure of the simple PI control loop. The difference can be noted at the level of $K_p$ and $K_i$ factors which are multiplied by the (local) channel load share factor expressed as CLS. It is also noticeable that CLS is calculated by dividing the measured channel load by the number of neighbors plus one which correspond to the target vehicle itself. It is also important that the $K_p$ and $K_i$ factors are dynamically recalculated (retuned) by means of the CLS factor during the observation period. Despite this dynamic feature the CLS approach suffers from the same initial tuning of the $K_p$ and $K_i$ factors which means that these parameters are specific to the characteristics of the target network.

![Figure 4.8: PI controller with channel load share information.](image_url)
As shown in Figure 4.8 the parameters of the simple PI control loop with CLS are the proportional $K_P$ factor, integral $K_I$ factor and the reference channel load $sp$. The latter is compared to the measured channel load which is periodically calculated to determine the error value $e(t)$. Finally, the TX power value runs from the lowest and highest limits determined by ETSI as it is explained in Chapter 5. Additionally the CLS value is periodically calculated to keep track of the level of responsibility of a given vehicle.

Chapter 5 presents the results of our simulations towards the evaluation of the existing and proposed mechanisms that we presented in this chapter. The effectiveness of the four mechanisms is assessed under the selected network performance metrics.
Chapter 5

SIMULATIONS RESULTS AND CRITICAL EVALUATION

This chapter contains the results of the various simulation runs that were executed to test and compare the performance of the existing and the proposed approaches. Similar parameters and scenarios were used in pursuit of fair comparisons among the simulations. Section 5.1 covers the parameters and setup of the simulation environment, Section 5.2 explains the performance metrics, Section 5.3 presents the preliminary experiments we have executed. Section 5.4 presents the simulation results for the different scenarios and options considered. Finally, Section 5.5 contains concluding remarks and a critical evaluation of the results obtained in this chapter.

5.1. Parameters and setup of the simulation environment

Chapter 3 already presented the system model and the scenarios considered for this thesis work while Chapter 4 focused on the presentation of the existing and proposed approaches (algorithms) to be evaluated. Based on that, the purpose of this section to explain how the system model and algorithms were integrated to set up the simulation environment.

5.1.1. Vehicular scenario

In the first place, we selected a vehicular scenario with highway properties. For this scenario we chose that only vehicles are present and are distributed in a single lane with no obstruction from buildings or other side road elements. When applicable (mobility scenarios), vehicles move in one direction traveling from east to west in a single queue with no overtake maneuvers occurring.

Vehicular mobility is important to address as it was used to classify the sets of simulations executed and presented in this thesis report. The simulation results are divided based on the types of vehicular mobility options considered. As it was mentioned in Section 3.2, we considered four types of vehicular mobility: homogeneous static, heterogeneous static, homogeneous mobile and heterogeneous mobile. In the case of mobile vehicles, we used IDM as car-following model. As we explained before, our simulations are conducted by using the ns-3 simulator in combination with SUMO for vehicular mobility generation (IDM model included).

Table 5.1 presents a summary of the parameters of the vehicular scenario.
5. Simulations results and critical evaluation

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Type of vehicles</td>
<td>Car</td>
</tr>
<tr>
<td>Number of vehicles</td>
<td>100</td>
</tr>
<tr>
<td>Size of vehicles</td>
<td>5 m</td>
</tr>
<tr>
<td>Inter-vehicle distance</td>
<td>10 m to 15 m</td>
</tr>
<tr>
<td>Mobility</td>
<td>Yes (when applicable)</td>
</tr>
<tr>
<td>Car following model</td>
<td>IDM (when applicable)</td>
</tr>
<tr>
<td>IDM Desired velocity ($v_0$)</td>
<td>100 km/h</td>
</tr>
<tr>
<td>IDM Minimum safe time headway ($T$)</td>
<td>1.0 seconds</td>
</tr>
<tr>
<td>IDM Minimum bumper-to-bumper distance ($s_0$)</td>
<td>2 m</td>
</tr>
<tr>
<td>IDM Acceleration ($a$)</td>
<td>1.0 m/s²</td>
</tr>
<tr>
<td>IDM Deceleration ($b$)</td>
<td>1.5 m/s²</td>
</tr>
<tr>
<td>Overtaking maneuvers</td>
<td>NO</td>
</tr>
<tr>
<td>Traffic in opposite direction</td>
<td>NO</td>
</tr>
</tbody>
</table>

Table 5.1: Vehicular scenario parameters.

5.1.2. Communication parameters
We have stated throughout this thesis work that the main objective is the improvement of the mechanisms utilized by ETSI DCC towards VANETs communications optimization. For that reason, we selected the main communication parameters (Table 5.2) for the simulation experiments presented in this report in accordance to the standard documents published by ETSI. The standard document “Decentralized Congestion Control Mechanisms for Intelligent Transport Systems operating in the 5 GHz range” (ETSI TS 102 687) was considered as base as it contains the description of the DCC mechanisms and the communication parameters most commonly utilized [24]. The EDCA scheme relies on CSMA/CA along with a slotted Binary Exponential Backoff (BEB) mechanism for contention-based channel access and supports MAC-level QoS and prioritization of different data/traffic by defining multiple Access Categories (ACs) with different Contention Window (CW) and Arbitration Inter Frame Space (AIFS) values. More specifically for our thesis work, we use AC_BK as fixed AC which means that no traffic differentiation takes place. Table 5.2 shows the default values usually set for this kind of networks and used in this project.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Transmission technology</td>
<td>IEEE 802.11p</td>
</tr>
<tr>
<td>TX speed</td>
<td>6 Mbps</td>
</tr>
<tr>
<td>TX inter-message time</td>
<td>0.04 seconds to 0.1 seconds</td>
</tr>
<tr>
<td>TX power</td>
<td>-10 dBm to 33 dBm</td>
</tr>
<tr>
<td>TX range</td>
<td>9 m to 238 m</td>
</tr>
<tr>
<td>CAM size</td>
<td>200 bytes to 1000 bytes</td>
</tr>
<tr>
<td>Propagation loss model</td>
<td>Log distance</td>
</tr>
<tr>
<td>CCA threshold</td>
<td>-85 dBm</td>
</tr>
<tr>
<td>Path loss exponent</td>
<td>3</td>
</tr>
<tr>
<td>Reference distance</td>
<td>1 m</td>
</tr>
<tr>
<td>Reference loss</td>
<td>46.67 dBm</td>
</tr>
<tr>
<td>SlotTime</td>
<td>13 $\mu$s</td>
</tr>
<tr>
<td>SIFS\text{\text{Time}}</td>
<td>32 $\mu$s</td>
</tr>
<tr>
<td>CW min</td>
<td>15</td>
</tr>
<tr>
<td>CW max</td>
<td>1023</td>
</tr>
<tr>
<td>AC</td>
<td>AC_BK</td>
</tr>
<tr>
<td>AIFS\text{\text{N}}</td>
<td>9</td>
</tr>
<tr>
<td>TXOP</td>
<td>0</td>
</tr>
</tbody>
</table>

Table 5.2: Vehicular scenario parameters.
5.2. Performance metrics

Another important step in this thesis work is the selection of relevant performance metrics which allow the evaluation of the existing and proposed algorithms. We consider channel load (CL) as an important metric to observe as it is aimed to be controlled by the proposed algorithms. Packet delivery ratio (PDR) is our main evaluation metric which we aim to improve. The following subsections define channel load and PDR as the evaluated performance metrics in this report and explain the reasons for that choice.

5.2.1. Channel load

ETSI has defined for VANETs that the channel load perceived by a vehicle for a given signal threshold $S_{th}$ is specified as the fraction of time that the received signal level $S$ is above the threshold $S_{th}$ (both terms expressed in dBm units). $S_{th}$ refers to the CCA threshold which is used by the DCF and EDCA protocols to perform the CCA procedure and determine if a channel is busy, as explained in Chapter 2. Channel load, also known as the Channel Busy Ratio (CBR) in the literature, is of particular interest to this thesis project. ETSI has suggested a method to estimate channel load which can be explained based on Figure 5.1.

![Figure 5.1: Graphic representation of channel load calculation.](image)

Figure 5.1 exemplifies the measurement of channel load as stated by ETSI. This figure shows the channel load from three different perspectives. A given network is assumed to have five transmitting stations (or vehicles) with IDs ranging from 0 to 4. The first part (top of the figure) represents the transmission of packets by every station at different periods in time. It is assumed that every station has a different TX inter-message
time. Station number 4 does not perform any transmission. This part of the figure also indicates the busy periods which occur when overlapping transmissions are detected on the channel. In the figure, all vehicles are within each other’s TX-RX distance.

The second part of the figure (middle) shows the average signal level (measured in dBm) from the perspective of station 4 (which is considered as not transmitting). The purpose of this part of the figure is to look at busy periods from a measured signal level point of view. It can be observed that the average signal level detected on the channel by station 4 depends on the number of ongoing transmissions i.e. a higher number of transmissions translates into a higher average signal level. This part of the figure also shows the default $S_{th}$ (CCA threshold with a value of -85 dBm as defined by ETSI) and indicates when that threshold is surpassed by the average signal level $S$ measured by station 4. It is important to point out that when the CCA threshold is exceeded the channel is considered as busy.

The bottom part of the figure also analyzes the busy and idle periods but as a boolean channel busy indicator (CBI). This indicator is set to one when the CCA threshold is surpassed (as indicated by the middle part of the figure) or it is set to zero otherwise. The parameters determined by ETSI are also shown in this part of the figure: number of probes $N_p$, channel probe intervals ($T_p$), and measuring intervals ($T_m$). For simplicity, in this example $N_p$ equals to 5 probes. Channel load is calculated and averaged every $T_p$ interval and the track of values over the last $T_m$ interval is always maintained. The times for channel load calculation are also indicated in this part of the figure. As an example, only three calculation times are indicated to graphically show how channel load is computed as a moving average or sliding window every $T_p$ interval. It can be noted that only $N_p$ probes are taken into account for the average calculation performed at $T_m$ intervals, i.e. every $T_p$ interval the left most $N_p$ probe (older probe) is discarded while a newer probe is considered. It is important to notice that the channel load measurement must be implemented as a sliding window which calculates a “moving average” over measurement intervals of length $T_m$. This means that every time a $T_p$ interval has elapsed, an individual channel load value is determined and it is used to keep track of the average channel load measured over the last $T_m$ interval. In other words, channel load is an average of the last $N_p$ probes taken within a $T_m$ interval and it is updated every $T_p$ interval. Based on the previous interpretations we define channel load in a formal manner.

First we define CBI as an instantaneous boolean indication (1 or 0) of the communication channel status in time as shown in Equation 5.1:

$$CBI(t) = \begin{cases} 1 & \text{if } S(t) > S_{th} \\ 0 & \text{otherwise} \end{cases}$$

The following step is the actual definition of channel load. A given vehicle or station takes $N_p$ probes of the received signal strength uniformly spread over a measuring interval of length $T_m$. For this thesis report $N_p$ is equal to 1000 probes while $T_m$ is equal to 1 second. For all probes which are taken every $T_p$ seconds ($T_m$ divided by $N_p$) the average signal level $S$ is determined and then compared to the signal threshold $S_{th}$ to determine whether the channel is considered as busy or not. ETSI has set $S_{th}$ (or CCA threshold) to a default value of -85 dBm as shown in Table 5.2. This value is also considered for the simulations executed in this thesis work as stated in Table 5.2. Channel load can be then expressed as a theoretical moving average $CL(t)$ by Equation 5.2 and then as expressed in discrete time $\overline{CL}(t)$ by Equation 5.3. We specifically use the discrete time $\overline{CL}(t)$ version for our analysis in this thesis work.

$$CL(t) = \frac{1}{T_m} \int_{t-T_m}^{t} CBI(\tau) d\tau \quad (5.2)$$

$$\overline{CL}(t) = \frac{1}{N_p} \sum_{n=0}^{N_p-1} CBI(t-nT_p) \quad (5.3)$$
Figure 5.2 shows the channel load as a function of time (calculated every $T_p$ interval) and is calculated for station 4 based on the values of the channel busy indicator as plotted in Figure 5.1. As an example, the channel load at time 1 (value of 0.8) was obtained by calculating the average of the first five values of the channel busy indicator set to one, i.e. the first $T_m$ interval in Figure 5.1. It is clear that four values (out of five) of the channel busy indicator are set to one (channel busy) resulting in channel load of 0.8. It is also observable that two channel load values reach the maximum of 1 when all the samples of the channel busy indicator (in a $T_m$ interval) are set to one. Other channel busy ratio values of 0.6 and 0.4 are observable in this figure and are the result of different values of the channel busy indicator at given $T_m$ intervals.

Figure 5.2: channel load calculation.
5.2.2. Packet delivery ratio
ETSI defines packet delivery ratio (PDR) for a given station, as the ratio between the number of successfully received packets (provided that the SINR of 3 dB is accomplished for successful reception as stated in Chapter 3) by that station and the number of packets sent by a given source station as shown in Equation 5.4. For PDR we consider the total number of packets (sent and received) for the entire simulation time, i.e. this metric is calculated at the end of the simulation time. Moreover, we aim to eliminate the transient period for our channel load calculations by waiting until each station transmits at least once (accomplished after roughly 1 second as found during our simulation tests) before starting the collection of our metrics. In order to achieve that, for our simulations the stations in the vehicular network start their transmissions at different times.

For our thesis work we consider PDR as the most important metric to analyze the performance of VANETs. Therefore simulation results based on PDR are widely used in this chapter. Information about neighbor vehicles up to a certain distance (TX-RX distance) is valuable for safety applications in a vehicular scenario. Therefore it is desirable, for any vehicle, to achieve high PDR values with respect to nearby vehicles in order to receive updated CAMs and to take proper and quick decisions with the information contained on them, e.g. braking on time to avoid a collision with vehicles located upfront.

We base our considerations for PDR from the perspective of a source-destination pair of stations i.e. \( \text{PDR}(s,d) \). This means that for any given vehicle we count all CAMs successfully received from other vehicles (pairs) in the network. With this information we calculate PDR on a per pair basis. More formally, for every destination \( d \) we calculate PDR for every source \( s \) as described in the following equation:

\[
\text{PDR}(s,d) = \frac{\sum \text{CAMs from } s \text{ received at } d}{\sum \text{CAMs sent from } s}
\] (5.4)

5.2.3. Additional performance metrics
Other performance metrics enlisted below are considered in this thesis work:

- Average channel load. This metric refers to a time-average ratio of all the channel load values measured by a given station throughout the simulation time.

- Channel load share ratio. This metric refers to the channel load contribution of a given station with respect to nearby neighbor stations. As explained before, this metric is a fraction of the channel load and depends on the number of neighbor stations.

5.3. Preliminary experiments
This section presents a set of preliminary experiments we executed via the simulation tool (ns-3) only for IEEE 802.11p, our baseline approach. The purpose of these experiments is to explain the theoretical concepts presented throughout this thesis work and then later observe them from the point of view of simulation. The assumptions mentioned in this section are considered as essential for the simulation results that are later presented. We present these preliminary experiments mainly in terms of the channel load and PDR.

In order to exemplify and understand the measurement of channel load and PDR in a simple vehicular scenario, we use the topology shown in Figure 5.3. This consists of a static highway scenario with 100 vehicles (vehicles IDs ranging from 0 to 99) uniformly spread over a straight line with an equal inter vehicle distance of 10 m. The vehicles are distributed across a 1000 m stretch of highway (vehicle 0 is placed at \([x=0, y=0]\) coordinate and vehicle 99 is placed at \([x=990, y=0]\) coordinate).

![Figure 5.3: Simple 100-vehicles scenario.](image)

Regarding the communication parameters in this scenario, we assumed that CAM messages are transmitted in broadcast mode by using IPv4 as routing scheme to emulate CAMs behavior as we explained in Section
3.3. As we assumed IPv4 for the transmission of CAMs then the overhead added by MAC, IPv4 and UDP is also considered as 64 extra bytes in addition to the 1000 bytes of payload. As we also explained in Chapter 3, we decided that for our baseline simulations CAMs have a default payload size of 1000 bytes (other sizes are also considered), an inter message time of 0.1 seconds (i.e. 10 messages per second) and a TX speed of 6 Mbps. With those parameters in mind, the transmission time of every CAM from source to destination has a value of 1.353 ms as shown by Equation 3.6.

5.3.1. Theoretical calculation of channel load
In this section we present a theoretical calculation of the channel load. For that purpose we considered the CAM transmission time calculated above. In accordance to ETSI DCC literature, we assume values of 33 dBm for TX power and 0.1 seconds for inter-message time as fixed for the 100 vehicles shown in Figure 5.3. Our next step is the calculation of the TX-RX distance for CAMs transmissions corresponding to such TX power value by using Equation 3.3 related to the calculation of the path loss (at a distance $d$) for the log-distance propagation model presented in Chapter 3.

From this equation, the parameter $d$ corresponds to the TX-RX distance and can be found if the other parameters mentioned above are provided. As we explained before, for this thesis project we consider the values shown in Table 5.2 resulting in a TX-RX distance of 238.45 m as calculated previously.

After the scenario and communication parameters are set up, it is possible to determine the channel load from the point of view of the vehicle located at the center of Figure 5.3, i.e. the vehicle with ID 49. This vehicle, as the others, are capable of “listening” to transmissions of 46 neighbor vehicles based on their maximum TX-RX distance (238.45 m) and the inter vehicle distance considered (10 m). This means that vehicle ID 49 is able to receive transmissions from 23 vehicles located at its front and from 23 vehicles located at its rear, i.e. its possible neighbors. In fact, the location of this vehicle represents the worst case in terms of channel load as it has the maximum possible number of neighbors. Therefore, assuming that each vehicle starts and maintains CAMs transmissions in broadcast mode and that no overlap among these transmissions occur, a maximum channel load can be calculated as shown in Equation 5.5.

$$\text{Max. channel load} = \#\text{neighbors} \times \text{CAMs per second} \times \text{CAM transmission time}$$

$$= 46 \times 10 \times 0.001353$$

$$= 0.62238 \text{(5.5)}$$

In order to intuitively calculate the minimum value for channel load in this network, then we focused on the edge vehicles (ID 0 and ID 99), i.e. vehicles located at the left and right most positions in the network shown in Figure 5.3. Both vehicles are able to receive transmissions of up to 23 neighbor vehicles as they only have neighbors at the rear or at the front. Therefore for such edge vehicles, the measured channel load value is expected to be half of that measured for the center vehicle, i.e. 0.3119.

In reality, the measured maximum channel loads with IEEE 802.11p will be smaller: the hidden-terminal problem can lead to transmission overlaps (and thus a reduction in channel load compared to the theoretical load). Moreover, IEEE 802.11p channel-access algorithms cannot always avoid simultaneous transmissions, even if vehicles are in each-other’s transmission TX-RX distance.

5.3.2. Simulation of channel load
Now that the theoretical calculation of channel load has been demonstrated, we move on to the simulation environment (ns-3). We consider the simple scenario used in the previous subsection consisting of 100 static vehicles together with the parameters mentioned in Table 5.3. It is important to mention beforehand that the starting times for transmissions were randomized among all vehicles, therefore a transient or stabilization period takes place at the beginning of the simulation. Regardless of the inter-message times the total simulation time that we considered for the experiments presented in this chapter is 2000 seconds.

Figure 5.4 shows the resulting channel load obtained after the careful implementation in ns-3 of this metric according to Equation 5.1. For readability, only the values of 10 representative vehicles and the first 500 seconds are shown. As it was expected, the simulated channel load differs from the theoretical calculation.
5. Simulations Results and Critical Evaluation

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Transmission technology</td>
<td>IEEE 802.11p</td>
</tr>
<tr>
<td>TX speed</td>
<td>6 Mbps</td>
</tr>
<tr>
<td>TX inter-message time</td>
<td>0.1 seconds</td>
</tr>
<tr>
<td>TX power</td>
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</tr>
<tr>
<td>TX range</td>
<td>238 m</td>
</tr>
<tr>
<td>CAM size</td>
<td>1000 bytes</td>
</tr>
<tr>
<td>Propagation loss model</td>
<td>Log distance</td>
</tr>
<tr>
<td>CCA threshold</td>
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</tr>
<tr>
<td>Path loss exponent</td>
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<tr>
<td>Reference distance</td>
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</tr>
<tr>
<td>Reference loss</td>
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</tr>
<tr>
<td>SlotTime</td>
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</tr>
<tr>
<td>SIFS Time</td>
<td>32 µs</td>
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<td>CW min</td>
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<tr>
<td>CW max</td>
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</tr>
<tr>
<td>AC</td>
<td>AC_BK</td>
</tr>
<tr>
<td>AIFS N</td>
<td>9</td>
</tr>
<tr>
<td>TXOP</td>
<td>0</td>
</tr>
<tr>
<td>Simulation time</td>
<td>2000 seconds</td>
</tr>
</tbody>
</table>

Table 5.3: Communication parameters for channel load experiments.

because for the simulated scenario overlaps among transmissions occur. However it is still evident that for vehicles located closer to the center of the network, the channel load is higher: the channel load ranges from approximately 0.51 for vehicle ID 49 to a value of 0.27 for vehicles ID 0 and ID 99. Those values represent the overall maximum and minimum channel load values observable for this network. In particular, the maximum channel load does not surpass the maximum theoretical value calculated in Equation 5.3 giving plausibility to the correct implementation of this metric.
In this experiment it is also observable that channel load values are maintained during the entire simulation time. This behavior was expected as no channel load control mechanism has been implemented yet.

Figure 5.4: Channel load for 100 vehicles in homogeneous static scenario
(TX inter message time: 0.1 seconds, TX power: 33 dBm, CAM size: 1000 bytes)
5.3.3. Simulation of PDR

Our next step regarding PDR is its simulation and analysis via ns-3. Again, we considered the parameters shown in Table 5.4. For readability purposes, PDR is commonly represented as a function of TX-RX distance, taking into account only half of the vehicles or stations in the network. From this point and on, we choose to focus only on half of vehicles located in front of vehicle ID 49, i.e. vehicles with ID ranging from 50 to 99. Given the symmetry of the network scenario which consists of a straight line of vehicles we expect that our results are similar for both sides and therefore we choose to focus on results from the perspective of a given vehicle with other vehicles ahead.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
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<tbody>
<tr>
<td>Transmission technology</td>
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<tr>
<td>TX speed</td>
<td>6 Mbps</td>
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<tr>
<td>TX inter-message time</td>
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<tr>
<td>TX power</td>
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<tr>
<td>TX range</td>
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<tr>
<td>CAM size</td>
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</tr>
<tr>
<td>Propagation loss model</td>
<td>Log distance</td>
</tr>
<tr>
<td>CCA threshold</td>
<td>-85 dBm</td>
</tr>
<tr>
<td>Path loss exponent</td>
<td>3</td>
</tr>
<tr>
<td>Reference distance</td>
<td>1 m</td>
</tr>
<tr>
<td>Reference loss</td>
<td>46.67 dBm</td>
</tr>
<tr>
<td>SlotTime</td>
<td>13 (\mu)s</td>
</tr>
<tr>
<td>SIFSTime</td>
<td>32 (\mu)s</td>
</tr>
<tr>
<td>CW min</td>
<td>15</td>
</tr>
<tr>
<td>CW max</td>
<td>1023</td>
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<tr>
<td>AC</td>
<td>AC_BK</td>
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<td>AIFSN</td>
<td>9</td>
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<tr>
<td>TXOP</td>
<td>0</td>
</tr>
<tr>
<td>Simulation time</td>
<td>2000 seconds</td>
</tr>
</tbody>
</table>

Table 5.4: Communication parameters for PDR experiments.

Figure 5.5 shows the results of the PDR calculation by simulation with ns-3. The purpose of this figure is to demonstrate the effects that different CAM inter-message times have on PDR. Even though algorithms that use different inter-message times for channel load control (rate control) are not the main target of this thesis work, it is important to recall that ETSI DCC makes use of this feature. In order to obtain a representative and readable example, the simulated network is reduced to only 10 vehicles inter spaced with a distance of 50 m. In any case an optimal PDR of 1 is difficult to observe given the large number of messages transmitted as it will later addressed in this subsection. This figure shows the PDR of the center vehicle (ID 4) in this small network with respect to its right hand neighbors (IDs 5 to 9). Given the fact that a TX power of 33 dBm is assumed from Table 5.4, the TX-RX distance has still a maximum value of 238 m as it has been stated throughout this report. Therefore, only transmissions originated from distances smaller than 238 m are receivable by vehicle 4.

A closer look into Figure 5.5 shows the ideal case for PDR (unity value) when vehicles transmit with an inter message time of 0.1 seconds (10 messages per second) corresponding to the red line. For this case, it is observable that the only limitation to obtain an ideal PDR is the distance between source and destination. No CAMs are received from vehicle 9 located at a distance of 250 m (beyond the TX-RX distance of vehicle 4). It is also evident that the mechanisms used by IEEE 802.11p for medium access control are sufficient to handle the amount of traffic in the communication channel. This figure also includes the cases for smaller inter-message times represented by the other curves in color green and blue magenta. Obviously, PDR is dramatically affected when the inter-message time is decreased which means that more CAMs are sent per second even for such a small network. As a result more CAMs transmissions take place if the inter-message times are decreased which consequently increase the probability of collisions. In these scenarios, IEEE 802.11p mechanisms are not sufficient to maintain the network performance. For these set of tests we obtain results for
channel load in accordance to the level of congestion induced by different inter-message times i.e. the highest channel load values when using the smallest inter-message times as the number of CAMs is consequently increased.

With Figure 5.6 we aim to exemplify the effects on the PDR when different TX power values are used for CAMs transmissions. For this example, we set the size of the network to the default of 100 vehicles that we commonly use in this report. We measure the PDR for vehicle ID 49 with respect to its right hand side neighbors. Again, we considered the inter-vehicle distance as 10 m therefore vehicles are distributed across a 1000 m road. As we have mentioned, the PDR is greatly affected by high channel load, delays and collisions even for medium size scenarios where vehicles transmit with “large” inter-message times. For this example, we fixed the default inter-message time to 0.1 seconds while we varied the TX power values. For a TX power value of 33 dBm (magenta line) PDR is clearly affected, in this case only a few CAMs are received for the shortest TX-RX distance. In the case of lower TX power values (lines green and blue), PDR is slightly improved at the cost of a smaller TX-RX distance. The smallest TX power value (represented by the red line) offers the highest PDR but only for the closer neighbor vehicle located 10 m away. From this figure it is possible to observe that by using low TX power values a given vehicle’s TX-RX distance is reduced and therefore it has fewer neighbors. Moreover, fewer collisions occur as fewer transmissions take place from that vehicle’s perspective. Even though PDR can be analyzed from other perspectives like application layer, for our comparisons we value curves (cases) based on the lowest observed PDR for TX-RX distances up to 50m. Hence the best curve (case) is that with the ‘max-min PDR’, i.e. the highest value of the lowest observed PDR.
This example is key for this thesis project as the proposed approaches aim to improve PDR values. It is important to recall that the purpose of obtaining high PDR values in a vehicular network is to achieve that CAMs are successfully received by all vehicles within a certain TX-RX distance. Another parameter affecting the performance of these kind of networks is CAM size because the larger the message to be transmitted is then the longer TX time it will take and the higher probability for collisions occur. CAM size will be later addressed on our simulation set up parameters.

Figure 5.6: PDR for different TX power values.
5.4. Simulation results

This section presents the results obtained from the simulation tool (ns-3), in terms of the performance metrics already presented, for the existing and proposed approaches introduced in Chapter 4 and mentioned throughout this thesis work:

- Simple IEEE 802.11p (NO TPC). Further referred to as “IEEE 802.11p”.
- ETSI Decentralized Congestion Control. Further referred to as “ETSI DCC”.
- TPC with simple PI control loop. Further referred to as “TPC PI”.
- TPC with PI control loop and channel load share information (CLS). Further referred to as “TPC CLS”.

We use two dimensions to test the performance of the algorithms (if any) corresponding to each of the existing and proposed approaches. The first dimension corresponds to different vehicular mobility conditions (introduced in Chapter 3) in order to analyze how the algorithms react under unrealistic and realistic scenarios:

- Homogeneous and static inter-vehicle distances (static vehicles). Further referred to as “Homogeneous/static distances”.
- Heterogeneous and static inter-vehicle distances (static vehicles). Further referred to as “Heterogeneous/static distances”.
- Homogeneous and static inter-vehicle distances (mobile vehicles). Further referred to as “Homogeneous/static distances (mobile vehicles)”.
- Heterogeneous and dynamically changing inter-vehicle distances (mobile vehicles). Further referred to as “Heterogeneous/dynamic distances (mobile vehicles)”.

As second dimension we use different CAM sizes (200, 500 and 1000 bytes) in order to observe the effects of the CAM size on the algorithms’ performance. As we mention before CAM size has a great impact on the network’s performance as it determines the TX time per CAM (the larger the size then the longer it takes for transmission and the higher the probability for collisions). The completed list of parameters we utilized for the various experiments are condensed in Table 5.5 as used in addition to the parameters shown in Table 5.1 (when applicable).

Given the large number of graphs produced by our experiments we decided to include, in Subsection 5.4.1, a highly detailed description and interpretation of the results obtained (for each of the approaches) by choosing only one type for each of the two dimensions presented above. This means that for the first dimension, vehicular mobility, we chose the scenario of homogeneous and static inter-vehicle distance (static vehicles) because it corresponds to the simpler and more stable scenario. For the second dimension, CAM size, we chose 1000 bytes. This subsection is subdivided by approach type.

In Subsection 5.4.2, we present the complete simulation results (including every dimension type) in a condensed fashion emphasizing the comparison in performance of the different approaches. This means we took into account every vehicular mobility scenario and every CAM size. For the sake of organization, we subdivided these results by vehicular mobility type.
### Table 5.5: Communication parameters for ns-3 simulations.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
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</thead>
<tbody>
<tr>
<td>Transmission technology</td>
<td>IEEE 802.11p</td>
</tr>
<tr>
<td>TX speed</td>
<td>6 Mbps</td>
</tr>
<tr>
<td>TX inter-message time</td>
<td>0.04 to 0.1 seconds</td>
</tr>
<tr>
<td>TX power</td>
<td>-10 dBm to 33 dBm</td>
</tr>
<tr>
<td>TX range</td>
<td>238 m</td>
</tr>
<tr>
<td>CAM size</td>
<td>200 to 1000 bytes</td>
</tr>
<tr>
<td>Propagation loss model</td>
<td>Log distance</td>
</tr>
<tr>
<td>CCA threshold</td>
<td>-85 dBm</td>
</tr>
<tr>
<td>Path loss exponent</td>
<td>3</td>
</tr>
<tr>
<td>Reference distance</td>
<td>1 m</td>
</tr>
<tr>
<td>Reference loss</td>
<td>46.67 dBm</td>
</tr>
<tr>
<td>SlotTime</td>
<td>13 $\mu$s</td>
</tr>
<tr>
<td>SIFSTime</td>
<td>32 $\mu$s</td>
</tr>
<tr>
<td>CW min</td>
<td>15</td>
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</tr>
<tr>
<td>AC</td>
<td>AC, BK</td>
</tr>
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<td>AIFS N</td>
<td>9</td>
</tr>
<tr>
<td>TXOP</td>
<td>0</td>
</tr>
<tr>
<td>Simulation time</td>
<td>2000 seconds</td>
</tr>
</tbody>
</table>
5.4. Detailed interpretation of simulation results (Homogeneous and static inter-vehicle distances, static vehicles)
In the homogeneous and static inter-vehicle distances vehicular mobility scenario vehicle positions are static, i.e. the vehicles do not move during simulation time. All vehicles have the same inter-vehicle distance with their front and rear neighbors.

IEEE 802.11p APPROACH
Figure 5.7 shows the instantaneous channel load percentage values for the static scenario considering 100 vehicles (only the results for 10 vehicles and the first 500 seconds are shown for readability), and fixed values of 0.1 seconds for inter-message time and 33 dBm for TX power. These results are presented earlier in this chapter but are included in this section for consistency. The channel load values observed in this figure correspond to the particular parameters previously selected. From this figure we observe how vehicles near the edges sense lower channel load values as a consequence of having less neighbors and therefore sensing less transmissions taking place which reduces the probability of collisions. As we observe vehicles for the edges through the center of the network we are able to see the increase of channel load values in accordance with more neighbors sensed and therefore collisions by these vehicles.

![Figure 5.7: IEEE 802.11p - Channel load for 100 vehicles (homogeneous/static distances)
(TX inter message time: 0.1 seconds, TX power: 33 dBm, CAM size: 1000 bytes)](image)

Figure 5.8 offers another perspective of the channel load values shown in the last figure. The data is now presented as the averaged value of channel load for every vehicle. This figure is useful to visualize more clearly the influence of the vehicles' position on the measured channel load value. Again the difference in channel load, of half of the maximum for the vehicles placed in the edges of the network, is evident.

The number of neighbors for a given vehicle is crucial to understand the regions of Figure 5.8 where the slope differs from zero (center). Vehicles placed in the edges have, as explained earlier, 23 neighbors at most while vehicles in the center have 46 neighbors at most. Therefore, the number of neighbors on each side tend to increase and equalize as vehicles are closer located to the center of the network. The greater and more equalized number of neighbors a given vehicle has, the more transmissions it will sense (taking into account the TX rate and TX-RX distance) which directly influences the channel load value. In this figure we also observe a breaking point in terms of average channel load values starting at vehicle ID 23 (left hand side).
and ID 75 (right hand side). For those vehicles the number of neighbors equalize on both sides which leads to the increase of channel load values as the vehicles analyzed are located nearest to the center of the network.

![Figure 5.8: IEEE 802.11p - Average channel load values vs vehicle ID (homogeneous/static distances)
(TX inter message time: 0.1 seconds, TX power: 33 dBm, CAM size: 1000 bytes)](image)

In terms of packet delivery ratio (PDR) the behavior of IEEE 802.11p is shown in Figure 5.9. For simplicity we consider PDR from the point of view of the network’s center vehicle (ID 49) with respect to the vehicles located ahead of it (east side) as representative. The TX-RX distance for this vehicle does not surpass the maximum calculated value (238 m) which means that CAMs transmitted from beyond that distance cannot be received. PDR is greatly affected by the high channel load sensed by this center vehicle. Moreover, it is worsened by factors like hidden node problem (and consequently collisions) and the physical boundary of the TX-RX distance. The choice for CAM size (1000 bytes) and inter-message time (0.1 seconds) is also determinant for the reduction in terms of performance. We stated in previous sections that combinations of larger CAMs sizes with short inter-message times lead to longer TX times and more frequent transmissions per CAM. Consequently the PDR performance becomes poor as collisions are more probable to happen. As it can be depicted, PDR is never optimal and has a value of 0.8 only for distances of less than 50 m, it drops to 0.2 for 150 m and it reaches zero for the maximum TX-RX distance. Another important factor for the resulting PDR values for IEEE 802.11p relies on the fact that the TX power is fixed for this approach. As IEEE 802.11p has no mechanism to alleviate channel load its performance degrades as congestion on the network increases even though the maximum TX-RX distance is reached (with very low PDR values). We can also observe that once the TX-RX distance is reached no more transmissions can take place due to physical limitations of the electromagnetic waves.
Figure 5.9: IEEE 802.11p - Packet delivery ratio of center vehicle (homogeneous/static distances) (TX inter message time: 0.1 seconds, TX power: 33 dBm, CAM size: 1000 bytes)
ETSI DCC APPROACH

ETSI DCC evaluation was achieved via the implementation of the state machine presented in Chapter 4. ETSI DCC relies on the TPC and TRC for channel load control. “Relaxed”, “active” and “restrictive” states make use of different values for TX power and TX inter message times. Therefore the values for TX power range from -10 dBm to 33 dBm while the values for TX inter message time range from 0.04 seconds to 1 second.

For readability purposes, Figure 5.10 shows a zoomed in version (only the first 25 seconds of the simulation is shown) of the channel load values and current DCC state measured for the center vehicle (ID 49). This figure shows the oscillatory behavior for the channel load value as a consequence of the switching action between the “active” (1) and the “relaxed” (0) DCC states. The changing values for TX power and TX inter-message time effectively maintain bounded channel load values at the price of oscillations. A closer look at the transitions of the current DCC state shows that the detection of high channel load values for at least 1 second, produces a fast reaction and switch to more conservative states. Switching from “relaxed” to “active” state decreases the current TX power and TX inter-message time due to the default parameters for latter state.

Stepping down to less conservative states (“active” to “relaxed”) requires that the channel load value is below certain threshold (0.15) condition for at least 5 seconds. In Figure 5.10 this behavior can be observed. The time spent in the “active” state before switching to “relaxed” is 5 times larger than the time spent in “relaxed” state before the switch to “active”. In this example a corner case is also noticeable. If one looks at any of the peaks of the channel load value it is clear that the 0.5 threshold, necessary to switch to “restrictive” state, is surpassed. However, as one of the rules states, the channel load value goes below 0.5 before the 1 second window elapses. By going deeper into the data, it is clear that the 0.5 threshold is surpassed only for 0.86 seconds as a response to the conservative measures taken by the “active” state. Therefore the “restrictive” state is never reached, at least never for the center vehicle.
Figure 5.11 plots the channel load of only 6 vehicles, again for readability purposes. In this figure, the different channel load levels are shown and the actions performed by the ETSI DCC state machine for its control are also shown. Even though the channel load measures are similar for every vehicle, it is observable that edge vehicles have the lower values. Despite of the fact that some vehicles almost reach the 0.6 channel load barrier, none of their DCC state machines reach the “restrictive” state. It is also observable that oscillations due to the switching among DCC states occur irrespective of the simulation time. This figure also shows that the maximum channel load is different depending on the location of the vehicle.
In terms of the time-average channel load, Figure 5.12 shows the effects of the ETSI DCC strategy per vehicle. Therefore, the number of vehicles in their neighborhood decreases as does the load of the communication channel. As it was explained before, vehicles in the edges of the network have the greater benefits in terms of channel load while vehicles in the center follow up in this category. The shape of this figure shows the relationship between channel load and the number of neighbors of the vehicles in this network. Vehicles in the edges sense fewer neighbors and therefore the lower channel load values. If we analyze vehicles starting from ID 0 and above, we can observe that as the number of neighbors increase on the right hand side of vehicles (for vehicles with ID 1 and above) channel load values also increase up to maximum for vehicles ID 25 to ID 30. For those vehicles the channel load is maximum as they sense the maximum number of neighbors given the decisions taken by the DCC mechanism. Vehicles in the center of the figure adopt a more conservative strategy by reducing their TX powers consequently sensing lower channel load values. Moreover the standing wave pattern in this figure can be explained by the negative feedback on the channel load as a consequence of the oscillating channel load values of each vehicle in the network and the fact that bounded conditions exist.

Figure 5.12: ETSI DCC - Average channel load (homogeneous/static distances)
(TX inter message time: 0.04 to 1 seconds, TX power: -10 to 33 dBm, CAM size: 1000 bytes)
In terms of PDR Figure 5.13 is helpful to analyze the cost of achieving low channel load values for vehicle ID 49 (center vehicle). For distances beyond 50 m, the performance decreases dramatically to less than 0.3 and it drops to zero at the maximum physical TX-RX distance. The low TX power levels used by the ETSI DCC “active” state help to lower the channel load values but also have an impact in the number of received CAMs. In comparison with IEEE 802.11p, the ETSI DCC scheme offers a lower performance in terms of PDR under the parameters of this particular scenario as a tradeoff for controlling channel load values. Therefore, at least in terms of PDR, ETSI DCC is not suitable for this particular vehicular scenario.

Figure 5.13: ETSI DCC - PDR for center vehicle (homogeneous/static distances)
(TX inter message time: 0.04 to 1 seconds, TX power: -10 to 33 dBm, CAM size: 1000 bytes)
TPC PI APPROACH
This section presents the values for channel load under the first proposed approach: TPC PI. Before discussing the results in the following figures it is important to mention the assumptions we make. In order to show the capabilities for channel load control of this proposed solution we allowed TX values usable by the control loop ranging from 50 dBm to -50 dBm. These values are not realistic and would not be achievable in any scenario. However, this range is useful to demonstrate the operation of the implemented PI control loop. Another assumption for this figure is related to the simulation time. We used a total of 2000 seconds as simulation time. However, for readability purposes we decided to take a snapshot of the first 100 seconds of simulation time.

As described in Chapter 4, the proposed control loop aims to control channel load based on the manipulation of TX power values. The purpose is to stabilize the PI control loop towards the set point value which is referred as channel load reference (CLR) in this report. Given its simplicity, we select manual tuning as mechanism to find the optimal factors ($K_p$ and $K_I$) for the PI controller for a channel load reference (or set point) of 0.3. As we later explain this reference value was found after executing the different simulations. At different channel load reference values we choose to run ten simulation sets each with ten simulation subsets for $K_p$ and $K_I$. For the first set we choose a fixed value of 1 for the $K_I$ factor and for each of the subsets we vary the $K_p$ factor (between 1 and 0.1). For the next set we choose a fixed value of 0.9 for the $K_I$ factor while running the corresponding subsets with different values for the $K_p$ factor and so on. In total ten sets (different values for $K_I$) of ten simulation subsets (different values for $K_p$) are executed to find the optimal values for these PI control loop factors. TX inter message times are set and fixed to 0.1 seconds as this approach excludes TRC.

Figure 5.14 shows only the relevant results of the control loop tuning taking into account only vehicle ID 49 (center vehicle) at reference channel load of 0.3 for different $K_p$ and $K_I$ factors. We fix $K_p$ to a value of 0.9, then $K_I$ we vary it until finding that a value of $K_p=0.9$/$K_I=0.5$ represents the ideal combination of these two parameters. As we can observe in this figure, the combination $K_p=0.9$/$K_I=0.9$ represented by the red line shows up to three overshoots in channel load before stabilizing the value; the combination $K_p=0.9$/$K_I=0.7$ represented by the green line reduces the overshoots to two events; the combination $K_p=0.9$/$K_I=0.5$ represented by the blue line shows an slight undershoot but control channel load sooner than the previous combinations. Finally the combination $K_p=0.9$/$K_I=0.3$ represented by the magenta line increases the undershoot effect while converging later than the optimal combination. At this point it is possible to mention that despite of controlling channel load more efficiently, our PI control based approach is not flexible to cover more network scenarios than the selected for this thesis work and depends greatly on the sensitivity of the tuning parameters. We can also state that the development and integration of a self-optimization process to find the right $K_p$ and $K_I$ factors would be quite useful to make our approach adaptable to network changes. For this thesis project we focus on static PI controller tuning. Moreover our approach depends on other factors as the propagation model used (log-distance model in this case). This means that for other propagation models we expect different results for the control loop tuning process.
Figure 5.14: TPC PI – Control loop factor tuning (homogeneous/static distances)
(TX inter message time: 0.1 seconds, TX power: -50 dBm to 50 dBm, CAM size: 1000 bytes)
Figure 5.15 finally shows the channel load for 100 vehicles (only 10 vehicles are shown) using the optimal $K_P = 0.9$ and $K_I = 0.5$ values with a reference channel load of 0.3. In this figure, it is possible to observe that the PI control loop reacts to the initial channel load value reaching values of 0.6 given the initial value of 33 dBm for TX power assumed for every vehicle. As it was mentioned above, we set the reference channel load of the PI control loop to a value of 0.3. Therefore the PI control loop aims to reach this reference value by applying different TX power values. The system reaches a stability point on the reference value roughly at 10 seconds of the simulation time, which is also related to the selection of the $K_P$ and $K_I$ factors i.e. the right combination of those factors influence the overshoot effect and therefore the stabilization time of the target variable. Once the stability point is reached, it is maintained until the end of the simulation time.

Figure 5.15: TPC PI – Ideal channel load control (homogeneous/static distances)
(TX inter message time: 0.1 seconds, TX power: -10 dBm to 33 dBm, CAM size: 1000 bytes)
In order to present the effectiveness of the TPC PI control loop under more realistic conditions we set the available TX power values ranging from -10 dBm and 33 dBm in accordance to the parameters used by ETSI and stated in Table 5.2 under the scenario parameters stated in Table 5.1. Figure 5.16 shows the effects of using such TX power range. In this figure, it is possible to observe that only few vehicles in the network are capable of approximating to the desired channel load reference value of 0.3. This behavior relies on the fact that every vehicle chooses different TX power values depending on the channel load that they individually sense. In fact we can observe the effects of the selected TX power values for the measured channel load. In this case edge or near edge vehicles sense the lowest channel load values because they have fewer neighbors in comparison with center vehicles. After analyzing the TX power values selected by each station during simulation time (we do not include these results in this thesis report) we observe that the edge vehicles select the highest TX power values as a result of the low channel load values sensed by the PI control loop. As a result edge vehicles’ channel load values do not surpass the 0.2 barrier. Despite the difference in channel load, the control and stabilization features of the PI control loop are observable. As it will be later explained, PDR is still benefited under these values of channel load.

Figure 5.16: TPC PI - Channel load (homogeneous/static distances)
(TX inter message time: 0.1 seconds, TX power: -10 dBm to 33 dBm, CAM size: 1000 bytes)
Figure 5.17, Figure 5.18 and Figure 5.19 below show relevant results for the test we execute during the PI control loop tuning process. The simulations run for this purpose were executed for a period of 100 seconds for simplicity given the large amount of time required to execute tests with different parameters combinations. Each figure shows the PDR against different TX-RX distances assuming a fixed channel load reference value and different combinations of the $K_P$ and $K_I$ parameters. Our purpose is to demonstrate that the tuning of the PI loop requires the test of different combinations of the mentioned parameters. Therefore choosing the wrong parameters leads to non-optimal PI control loop. As a result PDR values are also affected by a wrong PI control loop tuning as shown by Figure 5.17 and Figure 5.19. For the present scenario characteristics Figure 5.18 shows that $CLR = 0.3$, $K_P = 0.9$ and $K_I = 0.5$ represents a suitable combination because the PDR values obtained are higher than the obtained for other combinations. Having to set the PI control loop parameters upfront, as we have stated before, is a main drawback of our PI control loop approach.
Figure 5.18: TPC PI loop tuning for CLR of 0.3 (homogeneous/static distances)
(TX inter message time: 0.1 seconds, TX power: -10 dBm to 33 dBm, CAM size: 1000 bytes)
Figure 5.19: TPC PI loop tuning for CLR of 0.1 (homogeneous/static distances)
(TX inter message time: 0.1 seconds, TX power: -10 dBm to 33 dBm, CAM size: 1000 bytes)
5.4. Simulation Results

In terms of the time-average channel load Figure 5.20 helps to show the effects in channel load of the selection of TX power made by each vehicle. In order to obtain this figure, we use a simulation time of 2000 seconds for more refined results. From this figure it is possible to observe that the vehicles in the network can be clustered based on their behavior in terms of TX power selection. This behavior is already observable in the ETSI DCC scenario presented earlier. In general our approach registers lower channel load averages in comparison with IEEE 802.11p because of the non-existing channel load control and reduction strategy of the latter. In comparison with ETSI DCC our approach registers higher channel load averages due to the considerable time spent by the latter on restrictive states. We also observe that the number of neighbors influences the measured channel load values by every vehicle. Again, as the vehicles are analyzed from edge to center positions they register more neighbors and consequently higher channel load values up to a break point (vehicles ID 30 and 70). After that point center vehicles adopt a more conservative strategy and tend to lower channel load values. Moreover a group of 10 near-to-edge vehicles on both sides sense in average a low channel load value of 0.2. The shape of this figure is also related to the TX power values chosen by vehicles in pursuit of controlling channel load. As we can see from Figure 5.16, edge vehicles only reach channel load up to 0.2 even though they use the highest TX power values. For the next block of 10 vehicles (IDs 20 to 40) we observe that the minimum TX power values are chosen. This pattern repeats for the next 10 vehicles (IDs 40 to 60) which means that the highest TX power values are chosen again however the (average) channel load values cannot be reduced as much as they were reduced for the edge vehicles. This behavior can be explained by the fact that more interference is sensed by those vehicles as they have a maximum number of neighbors. The last two blocks of vehicles continue with the pattern of high and low TX power values selection.

Figure 5.20: TPC PI - Average channel load (homogeneous/static distances)
(TX inter message time: 0.1 seconds, TX power: -10 dBm to 33 dBm, CAM size: 1000 bytes)
Figure 5.21 shows the results for the TPC PI control loop approach in terms of the PDR for $CLR = 0.3$, $K_P = 0.9$ and $K_I = 0.5$. The simulation we use for this experiment is 2000 seconds. This figure shows the benefits and drawbacks of this TPC PI. First, we can observe that the PDR is improved and reaches near optimal values up to a TX-RX distance of 100 m. Secondly, it is evident that CAMs transmitted by vehicles located farther than 100 m are not received. The reason for this improvement relies on the vehicles spending time in actual transmissions by choosing high TX power values while avoiding high channel load values at the cost of a reduced TX-RX distance. Later in this chapter, we present comparisons with respect to the other approaches. For now, it is useful to recall that the main objective of this thesis report is the optimization of VANETs in terms of metrics like PDR which has been clearly improved in this scenario.

Figure 5.21: TPC PI - PDR for center vehicle (homogeneous/static distances)
(TX inter message time: 0.1 seconds, TX power: -10 dBm to 33 dBm, CAM size: 1000 bytes)
5.4. SIMULATION RESULTS

TPC CLS APPROACH

In Chapter 4 we introduced another proposed approach which makes use of the concept of channel load share to improve the TPC PI control loop approach. As it was explained before, this approach assumes that the contribution of vehicles in a given VANET for the communication channel load should be constantly calculated, i.e. channel load share (CLS). The actions taken by vehicles should also be in accordance to their level of responsibility on channel load. This means that more aggressive actions should be taken by vehicles with a bigger responsibility. Channel load share values are then utilized in the TPC PI control loop as a factor which dynamically impacts the tuning parameters: $K_I$ and $K_P$. This section presents the results of TPC with PI control loop with channel load share.

For consistency and comparison purposes, we use the same parameters as for TPC PI control loop and therefore channel load $CLR = 0.3$, $K_P = 0.9$ and $K_I = 0.5$. Again, the simulation time used for this experiments was 2000 seconds but a zoomed in version showing 100 seconds is shown for readability reasons. Figure 5.22 shows the channel load for 10 out of the 100 vehicles in the network. After an initial overshoot the PI control loop is capable of stabilizing the channel load. In general, overshoot behaviors are undesirable for PI control loops as they represent states where too sensitive systems can be affected easily if the reference value is not reached in a proper manner. In the case of vehicular networks overshoots and therefore peaks in channel load values can lead to the loss of important CAM messages in a rapidly changing scenario. As it occurred with the TPC PI control loop approach, the reference channel load cannot be reached due to the range of TX power levels available for use by the vehicles in the network. The improvements of TPC with PI control loop in combination with CLS are not as clear from this figure but they will be evident in the upcoming examples.

![Figure 5.22: TPC CLS - Channel load](homogeneous/static distances)
(TX inter message time: 0.1 seconds, TX power: -10 dBm to 33 dBm, CAM size: 1000 bytes)

At this point we present the results of the calculation of channel load share for vehicle ID 49 (center vehicle). Figure 5.23 shows the channel load share calculated during the entire simulation time (left) which depends on the number of neighbors for that vehicle (right). We can observe that channel load share for vehicle ID 49 is a fraction of the channel load value previously measured for that vehicle in Figure 5.23. The reason for this is that the channel load share depends on the number of neighbors of vehicle ID 49. This shows that the contribution or responsibility of vehicle ID 49 is actually a small fraction of the calculated in Figure 5.23 and it varies depending on the number of neighbors. Therefore, as we suggest for this approach, its actions for channel load control should be according that contribution.
5. SIMULATIONS RESULTS AND CRITICAL EVALUATION

In terms of PDR, Figure 5.24 shows the benefits achieved by the PI control loop with CLS again for vehicle ID 49 (center vehicle). From this figure it is possible to observe that PDR keeps near the optimal value (PDR = 1) for a larger TX-RX distance than the TPC PI control approach. In this scenario, vehicle ID 49 is capable of receiving CAMs from vehicles located farther than 100 m. From this figure we observe that the CLS factor influences the behavior of the control loop to execute less drastic changes in TX power values. Consequently, high PDR values for a slightly longer TX-RX distance are observed in comparison with TPC PI. In this case we observe again a pattern on the TX power values selection by each vehicle similar to the observed for the TPC PI approach. The difference relies on the fact that the amount of vehicles choosing the lowest TX value is reduced. This behavior comes a result of the less drastic rate of change on the PI control loop induced by CLS. Therefore vehicles first observe its responsibility in terms of the current channel load and then change their TX power values accordingly.
5.4. Simulation Results

5.4.2. Performance comparison of simulated approaches

As we mentioned before, this subsection presents the complete results taking into account every option of the dimensions that we considered for the simulation experiments: four types of vehicular mobility scenarios and four CAM sizes. This subsection is organized by vehicular mobility type and for all four approaches or mechanisms. For each sub-subsection we present plots for PDR performance under different packet sizes and TX-RX distances.

Homogeneous/static distances (static vehicles)

This scenario represents the simpler mobility case (deeply analyzed in detail in the previous section) where vehicles do not move and are uniformly spread across the network topology.

Figure 5.25 is subdivided into three subfigures to show PDR for different packet sizes: 200, 500 and 1000 bytes as a function of the TX-RX range. In each subfigure IEEE 802.11p approach is represented by red lines, ETSI DCC by green lines, TPC PI by blue lines while TPC CLS by magenta lines. We can observe that the IEEE 802.11p and ETSI DCC approaches are degraded as the packet size is increased. As the former does not implement a channel control strategy, it is directly affected by collisions which are worsened by larger packet sizes. The latter controls channel congestion but sacrifices PDR performance. Both approaches achieve longer TX-RX ranges (when compared to TPC PI and TPC CLS) even though PDR decreases as the range increases. Despite the lack of a congestion control strategy, IEEE 802.11p shows high PDR performance and TX-RX range when small packet sizes are transmitted and worsens as they are increased. ETSI DCC proves to achieve high PDR on short distances (around 50m) but this performance decreases with the use of higher packet sizes. Moreover, the shape of ETSI DCC’s PDR line shows the effect of oscillating between states of the DCC state machine. In general, when the station operates in the “relaxed” state its TX-RX range is decreased but it is able to receive more packets from the closer neighbors as less interference from farther neighbors affect transmissions (higher PDR). The opposite case is shown when the station operates in the “active” state when a higher TX-RX range is achieved while collisions and interference (induced by an increased number of neighbors) is increased leading to poor PDR.

In the case of TPC PI and TPC CLS, PDR performance is nearly optimal for small packet sizes in comparison to IEEE 802.11p and ETSI DCC. For our thesis work we consider PDR as optimal when the values reach unity or near unity for a certain range. At least under this static vehicular scenario, we are able to show that the implemented PI control loop aiming to control channel load probes to stabilize it and consequently increase PDR performance up to certain TX-RX distance (around 100 m). As we have explained before, both algorithms aim to control channel load and when this goal is achieved TX power remains more stable which leads to avoid extreme cases where TX power values are too high or too low. Furthermore, TPC CLS extends the offered TX-RX distance when compared to TPC PI as an effect of the utilization of neighbor information to manipulate TX power values. For the TX power values we also obtain information but do not include those results for simplicity. From that analysis we can then observe that TX power variation depending on the level of responsibility of each station leads to less drastic changes in TX power while increasing the TX-RX distances. Finally we can observe that both approaches are only slightly affected when the packet sizes are increased. As a disadvantage, the TX-RX distances are not further increased (or decreased) when different packet sizes are used.
5. Simulations results and critical evaluation

![Packet size 200 bytes](image1)

![Packet size 500 bytes](image2)
5.4. SIMULATION RESULTS

Figure 5.25: PDR comparison for different packet sizes for static vehicles (homogeneous/static distances)
HETEROGENEOUS/STATIC DISTANCES (STATIC VEHICLES)

In this case, the vehicles in the network are also static while their inter-vehicle distance is randomized at the beginning of the simulation time and remains unchanged until the end.

Figure 5.26 shows the PDR with respect to different TX-RX distances. IEEE 802.11p approach shows consistent results as its performance shrinks as TX-RX distance and packet sizes increase. For ETSI DCC the same behavior as for homogeneous inter-vehicle distance remains because the performance is affected by TX-RX distance and packet sizes. In the case of the proposed TPC PI and TPC CLS approaches we observe some discrepancies in comparison with the last vehicular traffic scenario. TPC PI continues to achieve high PDR values with a slight decrease even for small packet sizes. Moreover, for TPC CLS we notice lower performance in comparison to TPC PI which is opposite to the results obtained for homogeneous/static distances (static vehicles). For this approach, as PDR is adversely impacted by higher packet sizes, TX-RX distances are higher in comparison to TPC PI. However PDR achieved by TPC CLS improves the value achieved by IEEE 802.11p and ETSI DCC at longer TX-RX distances.

Clearly for each mechanism the induced randomness in the distribution of vehicles affect the behavior of the algorithms (if any) because for some vehicles the interference caused by neighbors is higher than for vehicles with fewer neighbors. We observe that TPC CLS is less adaptable than TPC PI. A closer look into the average channel load and TX power selection by each vehicle help us to deduct the results obtained for TPC CLS. In terms of average channel load we observe that center and near center vehicles are not able to reduce channel load up to the values achieved by this mechanism for the homogeneous/static distances scenario. This effect is a consequence of the selection of TX power values by the vehicles which depends on the PI control loop and the CLS factor utilized. The TX power values for TPC CLS are not optimized because the PI control loop has a slower reaction due to the CLS factor and presents deficiencies to determine the responsibility of channel load in a scenario where vehicles are not equally spread. This means that for vehicles located at the edge or near the edge the number of vehicles can vary depending on the random process utilized at the beginning of the simulation time.
5.4. SIMULATION RESULTS

Figure 5.26: PDR comparison for different packet sizes for static vehicles (heterogeneous/static distances)
In this scenario the vehicles move across a straight road maintaining the inter-vehicle distance. As we explained before the combined capabilities of ns-3 and SUMO allowed the simulation of more realistic scenarios. In principle we observe consistency in the behavior of PDR values in comparison with the scenario of static and homogenous inter-vehicle distances.

Figure 5.27 shows PDR as a function of TX-RX distance for different packet sizes. As we have already mentioned, we observe that IEEE 802.11p and ETSI DCC are greatly affected by large packet sizes. TPC PI and TPC CLS achieve near optimal PDR values for a shorter TX-RX distance. TPC CLS improves the TX-RX distance values in comparison with TPC PI. Despite the mobility of the vehicles, the performance in PDR behaves similar to the static scenario due to the fact that all vehicles move at the same speed which only adds minor fading effects.
Figure 5.27: PDR comparison for different packet sizes for mobile vehicles (homogeneous/static distances)
HETEROGENEOUS/DYNAMIC DISTANCES (MOBILE VEHICLES)

This scenario covers the more realistic vehicular conditions in comparison with the previous cases because the vehicles involved now randomly change their velocity, accelerate and decelerate randomly in time as they move across the road. This behavior leads to changing inter-vehicle distances for the stations which are part of the network. For the previous scenarios (homogeneous/static distances for static vehicles, homogeneous/static for mobile vehicles and heterogeneous/static distances for static vehicles) the counting process of TX and RX CAMs required for PDR calculation becomes straightforward as the inter-vehicle distances remain constant for the entire simulation time even for mobile vehicles. Therefore PDR calculation is simplified to use the total CAMs sent by a transmitter vehicle and the total CAMs received by a receiver vehicle for a given TX-RX pair. As we explain throughout this thesis report we use the center vehicle (ID 49) as fixed receiver and calculate its PDR in relationship with other neighbor vehicles (IDs > 49).

In the case of heterogeneous/dynamic distances for mobile vehicles we implement a binning process to be able to correctly quantify the TX and RX CAMs related to the center vehicle and the corresponding PDR calculation. By binning process we refer to the definition of a data structure (bin) which contains the CAMs transmitted and received at different TX-RX distances. This is necessary because the inter-vehicle distances change over time. For example, a vehicle transmitting from 10 m away at time 0, might be transmitting from 30 m away at time 1. Therefore we divide our TX-RX distance axis (from the perspective of the center vehicle) into blocks of 20 m and then we assign a bin to each those blocks i.e. bin 0 corresponds to TX-RX distance 0-20 m, bin 1 corresponds to TX-RX distance 20-40 m and so on. Based on the detection of the position of a given vehicle at the moment of a CAM transmission and the position of the receiving vehicle at the moment of the CAM reception we are able to classify that particular CAM on the corresponding bin. With this in mind we build our PDR graphs as the relationship of PDR values with respect to TX-RX distance bins. For consistency we rename the x-axis as TX-RX distance as shown in Figure 5.28.

From this figure we observe that the PDR values achieved by the four approaches under this vehicular scenario are similar to the values achieved on the heterogeneous/static distances for mobile vehicles. For IEEE 802.11p the performance is still affected by the selected inter-message times and is worsened as the CAM sizes increase. ETSI DCC mechanism is also consistent with previous vehicular environments as it keeps on pursuing low and bounded channel load values at the price of low PDR values. In the case of our proposed mechanisms we again observe a diminishment on the PDR performance for TPC PI. For TPC CLS we can also confirm the lack of adaptability on unequally spread vehicles.
5.4. SIMULATION RESULTS

![Graph A: Packet size 200 bytes](image1)

![Graph B: Packet size 500 bytes](image2)
Figure 5.28: PDR comparison for different packet sizes for mobile vehicles (heterogeneous/dynamic distances)
5.5. Concluding remarks

We now offer a summary of the mechanisms and results presented in this chapter. We also analyze the implications of the results achieved by each of the four mechanisms presented from an application level point of view i.e. the benefits, drawbacks and choices of those mechanisms for possible VANET scenarios.

5.5.1. Chapter summary

In Section 5.1 we present the necessary parameters and considerations to run our simulation experiments. Regarding the simulation tool we select ns-3 simulator in combination with SUMO for vehicular traffic modeling. SUMO provides mobility for the vehicles in our network. This tool provides options to simulate homogeneous and heterogeneous inter-vehicle distances. Heterogeneous distances are achieved with the employment of the IDM model offered as an option in SUMO. We also present the vehicular scenario which basically consists of a single lane highway with 100 vehicles standing still or moving in the same direction with no overtaking maneuvers taking place. Regarding the vehicular traffic characteristics we select highway speeds up to 100 km/h. Given the fact that we consider static and mobile vehicles for our simulations we choose IDM traffic model to be used in the case of mobile vehicles. Therefore Section 5.1 presents also the IDM model parameters used in this thesis work, useful for the simulation set up for mobile vehicles.

Regarding the communication parameters we choose mainly IEEE 802.11p as the base transmission technology. Other fundamental parameters we choose, as recommended by ETSI DCC studies, are the TX speed of 6 Mbps, TX power between -10 dBm and 33 dBm, and the TX inter-message time between 0.04 seconds to 0.1 seconds. The propagation model we select is log-distance given its simplicity. Finally for the CAM sizes we choose packets of 200, 500 and 1000 bytes.

In Section 5.2 we introduced the performance metrics considered for the evaluation of the existing and proposed mechanisms: IEEE 802.11p, ETSI DCC, TPC PI and TPC CLS. First we introduce channel load as the metric to be measured and aimed to be controlled via the proposed mechanisms. This metric help us to evaluate the level of congestion of the communication channel. This means that higher channel load values correspond to high communication channel congestion. We measure channel load based on the rules described and adopted by ETSI in the context of VANETs. As stated by the literature, different factor in wireless networks contribute to high channel load values like hidden/exposed node terminal problems, collisions and medium access delays. For our experiments we propose to plot channel load as a function of time in seconds for each vehicle in the network. Regarding the communication channel use optimization we focus mainly on the PDR to evaluate the effectiveness of the existing and proposed mechanisms. PDR is defined as the ratio between the expected and the actual received CAMs for any vehicle or station. For our experiments we propose to plot PDR for one vehicle in the network as a function TX-RX distance in m. We also introduce secondary performance metrics like average channel load and channel load share to evaluate our experiments.

In Section 5.3 we executed preliminary tests to introduce our considerations for the calculation of channel load and PDR. For both metrics we consider the parameters stated in Table 5.3 and Table 5.4 for the vehicular scenario and communication establishment. Moreover we base these experiments in IEEE 802.11p mechanisms with the purpose of showing the adverse effects of high congestion of the wireless communication channel. We present theoretical calculation for those metrics and simulation runs executed via ns-3. For channel load we are able to demonstrate the maximum value for the selected vehicular scenario. For PDR we extend the experiments by varying the inter-message times and the TX power values. Those experiments allows to show the degradation of channel load and PDR under high congested communication channels.

In Section 5.4 we present our simulation results and comparisons of the existing and proposed mechanisms mainly focused on the control of channel load and the optimization of PDR for the four mechanisms considered in this thesis work:

- IEEE 802.11p.
- ETSI DCC.
- TPC PI.
- TPC CLS.
For that we subdivide that section to classify the results considering the mobility of the vehicles and inter-
vehicle distances among them:

- Homogeneous and static inter-vehicle distances (static vehicles).
- Heterogeneous and static inter-vehicle distances (static vehicles).
- Homogeneous and static inter-vehicle distances (mobile vehicles).
- Heterogeneous and dynamically changing inter-vehicle distances (mobile vehicles).

Again, we conduct our simulations based in ns-3. In the case of mobile vehicles we combine ns-3 and
SUMO features to implement the drivers’ behavior via the IDM traffic model. In this section we offer plots of
our simulations for channel load as function of time, PDR as function of TX-RX distance and PDR as function
CAM sizes at different TX-RX distances.

More specifically for each of the four mechanisms we first offer plots that show how those mechanisms
control (or not) channel load. In some cases we plot channel load for a single vehicle and in other cases
we plot this metric for several vehicles. For PDR we offer plots that which integrate the performance of the
four mechanisms focused on a single vehicle (center vehicle). Our purpose is to compare the performance
in terms of PDR as a function of TX-RX distance. We also offer results per mechanism in terms of average
channel load for a single vehicle. Finally, for PI CLS we present results in terms of CLS and the number of
neighbors for a single vehicle too. In order to obtain the results described above, we make use of the homo-
geneous and static inter-vehicle distances (static vehicles) scenario.

In the last subsection of Section 5.4 we include a comparison of the four approaches per vehicular sce-
nario, i.e. for static/mobile and homogeneous/heterogeneous scenarios. We choose to present the results
in this subsection in terms of PDR as a function of TX-RX and as a function of CAM sizes. Our intention is
to observe the PDR performance from different perspectives to be able to evaluate the four approaches in a
critical manner.

5.5.2. Critical evaluation
Throughout this chapter we evaluate the existing mechanisms IEEE 802.11p and ETSI DCC in comparison
with the proposed mechanisms TPC PI and TPC CLS. Given the selected scenario and communication pa-
rameters we are able to provide a critical evaluation about the benefits and drawbacks of each mechanism.
For this thesis work we aim to select a simple vehicular scenario and the basic required parameters to align
with ETSI’s recommendations for VANETS. This choice in itself already focus our results to one case of the
universe of possibilities when speaking about vehicular networks: single line roads with 100 vehicles. This
means that we discard, for simplicity, many options for road infrastructure like multi lane roads, road alti-
tude (other than flat) or road side vegetation as we do it also for many other vehicular traffic characteristics
like opposite direction traffic and different vehicle heights, etc. Therefore we consider that the effectiveness
of our proposed mechanisms should also be tested for other vehicular traffic and road infrastructure char-
acteristics. Regarding the communication parameters we also bound the possibilities up to the parameters
stated by ETSI with the purpose of beginning from a reference point and of obtaining useful comparisons.
However it would be interesting to test outcome of our proposed approaches for scenarios with different val-
ues of TX speed, TX power, CAM sizes, etc.

Regarding IEEE 802.11p we confirm that in general the lack of channel congestion mechanisms leads to a
visible saturation under high channel load situations. As we depict from our simulations, once the channel is
congested, channel load values keep at the maximum level as no actions are taken by the stations which are
part of the network. If we look at the average channel load we can observe that center vehicles measured the
larger values as they have more neighbors in comparison with near-edge or edge vehicles. In terms of PDR
we observe that for the possible TX-RX distance (given by the maximum TX power used) IEEE 802.11p shows
a decreasing performance if we look from the perspective of a single vehicle (center vehicle) out of the total
100 vehicles. This means if we analyze PDR from shorter to longer TX-RX distances (vehicles located near
and far from this vehicle) the performance decays despite CAMs are still received at the limit TX-RX distance.
We also observe that CAM sizes influence the performance of IEEE 802.11p in terms of PDR. In general, PDR
worsens as the size of CAMs is analyzed from smaller (200 bytes) to larger sizes (1000 bytes).

For ETSI DCC we observe that the control mechanism implemented by its state machine certainly leads to channel load control between bounded levels. However we confirm that a repetitive switching between “relaxed” and “active” states leads to oscillations of the channel load. It is also observable in terms of average channel load that center and edge vehicles achieve the lower channel load values provided that use low TX power values more frequently. Regarding ETSI DCC’s PDR performance, it also suffers from those oscillations because most of the time, stations do not transmit CAMs and instead spend time trying to control channel load. Despite that we observe that, for shorter TX-RX distances up to 50 m, PDR of the sample vehicle (center vehicle) achieves similar values as those achieved by IEEE 802.11p. For longer TX-RX distances ETSI DCC achieves lower PDR values. For other CAM sizes we do not observe differences in the performance of ETSI DCC. Therefore we can confirm the observations made in the literature about the oscillations induced by ETSI DCC mechanisms and therefore its capability to control channel load at the price of a low performance in terms of PDR (in comparison with ETSI DCC 802.11p).

Regarding TPC PI we also present simulation results in terms of channel load in order to show how this metric can be controlled by introducing control theory concepts, i.e. a Proportional-Integral control loop. Despite the improvement for channel load control while avoiding oscillations we confirm that finding the ideal tuning parameters is a demanding task which leads to a trial and error process to test different combinations. Therefore a major drawback when using PI control loops is the need of a control loop tuning process which is specific for the chosen vehicular scenario and communication parameters. However, we still observe an improvement for the control and stabilization of channel load control. In terms of average channel load we observe that center, near-edge and edge vehicles achieve the lower channel load values even when they use high TX power values. If we analyze PDR performance for center vehicle, we find that this metric achieves high values (near optimal) for up 100 m with respect to neighbor vehicles. For longer distances PDR drops to zero therefore the maximum physical distance that CAMs can reach (determined by the highest possible TX power value) is never achieved by TPC PI. Regarding CAM sizes, PDR performance decays as the size increases from 200 to 1000 bytes. Below we present a further discussion about the tradeoff between PDR, TX-RX distances and CAM sizes.

We also present the simulation results of TPC CLS, the enhanced version of TPC PI. As we have mentioned before our goal when conceiving a second version of TPC PI relies on the idea of enhancing the PI control loop by providing more information to the vehicles involved in the network. We also aim to test how the use of neighbors’ information can lead to take better decisions when controlling channel load and to obtain better results in terms of PDR. In general we find that channel load is controlled less efficiently than it is for TPC CLS with vehicles not reaching the channel load reference. This is caused by the smoothing process induced to the control loop by the CLS factor which depends on the number of neighbors registered. CLS factor certainly prevents that the changes in TX power values are less drastic than they are for TPC PI. Consequently, we observe that PDR is slightly improved compared to TPC PI (at least for scenarios where the inter-vehicle distances are heterogeneous) which is caused by stations maintaining certain TX power values sufficient to allow CAMs transmissions and receptions from longer TX-RX distances. In conclusion we observe that the benefits achieved are limited because PDR performance is only improved slightly with respect to TPC PI.

The last part of our simulation results section is dedicated to compare, in terms of PDR, the four mechanisms as a function of TX-RX distance and CAMs size. We also take into account the inter-vehicle distance set up to classify our results as we use this characteristic to create different vehicular conditions, some of them closer to real vehicular traffic behavior. From the results obtained by this classification we can already state that our proposed mechanisms show improvement in terms of PDR when the inter vehicle distances are static, i.e. they do not change in time. Therefore the next analysis is based on the assumption that the inter-vehicle distance is homogeneous during the simulation time which applies to: homogeneous and static inter-vehicle distances and homogeneous and static inter-vehicle distances. However as we state in the last section, for scenarios where the inter-vehicle distances are heterogeneous our proposed approaches do not perform as expected and in general the PDR values do not meet our expectations. Moreover, at application level we aim to explain how the mechanisms operate for different scenarios. For this we choose road safety applications and vehicular traffic control applications.
The most evident fact is that TPC PI and TPC CLS achieve the highest PDR values in comparison to IEEE 802.11p and ETSI DCC but also that for our proposed mechanisms CAMs reach a limited TX-RX distance of around 100 m. In contrast, IEEE 802.11p and ETSI DCC CAMs do reach this maximum TX-RX distance with an evident decreased PDR. Whether a CAMs’ PDR is more useful if it is optimal for a short TX-RX distance, or suboptimal for a longer TX-RX distance, relies on the requirements of the target application. As we stated on initial chapters, CAMs have been conceived for safety applications in the context of VANETs. This means that they are destined to improve vehicles awareness of their surroundings to provide other vehicles and drivers about other vehicles actions with the purpose of avoiding dangerous traffic situations. Therefore we consider that assuring high PDR values for CAMs being transmitted at a certain TX-RX distance is more valuable in terms of safety. This means that vehicles provided with enough up-to-date and complete information about potential dangers are more likely to avoid accidents. From our perspective TPC PI serves that purpose which is also improved by TPC CLS. Considering a different application, however, it may be also desirable to support longer TX-RX distances. For instance, in the case of vehicular traffic control, we consider that achieving high PDR values for shorter TX-RX distances is not crucial if we think of a scenario where vehicles stand at the road and receive information from beyond 100 m on the potential direction of vehicles ahead. In this case high level applications in the future might need information from longer TX-RX distances even if it is minimal to help solving traffic jams by rerouting vehicles’ directions. For this kind of applications IEEE 802.11p and ETSI DCC surpass TPC PI and TPC CLS.

In addition to the efficiency of TPC PI and TPC CLS for PDR at different TX-RX distances we also offer the CAM size dimension comparison. At this level we observe more closely that at different TX-RX distances PDR performance holds, at least for distances up to 100 m, for our proposed mechanisms while IEEE 802.11p and ETSI DCC suffer from variations when using larger CAM sizes. At application level, the use of different CAM sizes gives room for further discussion where inter-message times can also be included. At application level and recalling the examples we discuss for TX-RX distances we also analyze the effects of different CAM sizes and inter-message times. In the case of safety applications we consider that small sized CAMs in combination with small inter-message times are very important to achieve provided that these messages contain enough and prompt information to avoid a traffic accident. For those applications TPC PI and TPC CLS fulfill the requirements as they support high PDR values for different CAM sizes while the inter-message time is fixed to 0.1 seconds, while IEEE 802.11p becomes less appropriate given its lack of adaptation in pursuit of high PDR values at shorter TX-RX distances. ETSI DCC is in principle a mechanism design to adapt to different CAM sizes and inter-message times which could be used for safety applications. However from our experiments and for the scenarios proposed it does not show relevant results for safety applications. If we now analyze vehicular traffic control applications we might consider that large CAM sizes or less frequent CAMs, are more appropriate provided that these messages contains more information about traffic jams ahead and might help reducing high channel load at the same time as less messages would be transmitted per unit time. For this kind of applications, our results show that TPC PI and TPC CLS can fulfill the requirement of large CAM sizes while achieving high PDR values. In terms of larger or shorter inter-message times, the effectiveness of our proposed approaches is not possible to evaluate as the inter-message time is fixed. Given its limitations, IEEE 802.11p is also not appropriate even for less critical applications as it suffers in performance when inter-message times are reduced or CAM sizes become larger. ETSI DCC is again a good alternative for channel load control as it is adaptable in terms of inter-message times and CAMs sizes, however our simulation results show that this mechanism suffers when CAM sizes are increased.

Finally, we have to state that for inter-vehicle distances simulated more closely to real-life vehicular environments, i.e. dynamically changing with mobile vehicles, our proposed approaches TPC PI and TPC CLS are less adaptable to such random behavior of vehicles’ movement. From our simulation results and comparisons we observe that our approaches do not achieve the performance levels obtained for more ideal vehicle movement (inter vehicle distances do not changing over time) and end up being worse than applying plain IEEE 802.11p. ETSI DCC holds its properties for this kind of vehicular environments. Despite this drawback we consider that TPC PI and TPC CLS still contribute to find possibilities to enhance VANETS’ performance at least for the research on ideal scenarios. However the research on benefits of utilizing more information from neighbor vehicles and the optimization/automation of the PI control loop are potential directions for improvement for both mechanisms as we mention in Chapter 6.
CONCLUSIONS AND RECOMMENDATIONS
FOR FURTHER RESEARCH

This section concludes this thesis report and contains comments derived from the results presented in other chapters. Section 6.1 covers the conclusions of this thesis work while Section 6.2 contains the suggestions for further research topics.

6.1. Conclusions

Through the research work presented in this thesis report we aim to throw light on the improvement of congestion control of future vehicular wireless networks. We assess the possible use of a simple or enhanced proportional-integrating control loop (inspired by fundamental control theory concepts) over IEEE 802.11p VANETs, and further comparing it to the ETSI DCC scheme, as a solution to improve the *information exchange* between nearby vehicles, which is an essential basis for improving the actual traffic flows and associated traffic safety. The upcoming paragraphs aim to answer the research questions stated in the introductory Chapter 1.

Regarding the performance of ETSI DCC we implement its channel load control algorithm in pursuit of evaluating its performance and of comparing it against existing and newly proposed solutions. We mainly evaluate performance in terms of PDR experienced between vehicle pairs that are with 50m distance of each other. For that purpose we aim to control channel load of the communication channels of vehicular networks by improving the mechanisms proposed by ETSI DCC. First we compare the ETSI DCC algorithm with the baseline IEEE 802.11p scheme under similar conditions in terms of network set up. As we expect, the latter shows a poor performance in terms of PDR when collisions take place as a consequence of increasing the size of CAMs. This behavior is consistent with the lack of channel load control mechanisms in IEEE 802.11p. Throughout our experiments we observe that an increase in the number of neighbors and transmissions per unit of time have a negative influence on the performance of IEEE 802.11. ETSI DCC shows that channel load can be controlled and bounded. For TX-RX distances larger than 50 m PDR offered by ETSI DCC suffers from the effects of the oscillating behavior induced by the state machine internally implemented for channel load control. By means of our implementation we are able to reproduce the performance in terms of PDR of IEEE 802.11p and ETSI DCC as documented in the literature. In general, we find that IEEE 802.11p diminishes its PDR performance as channel load increases because it does not implement any control mechanism. In fact, ETSI DCC mainly focuses on keeping channel load bounded between reasonable limits which is observable from our experiments.

We develop and evaluate two approaches (TPC PI and TPC CLS) for channel load control inspired by principles of basic control theory. Both approaches are able to control channel load under static and mobile vehicles scenarios while keeping channel load in a near-steady state. This means that under both approaches the oscillating pattern seen with ETSI DCC is eliminated. TPC PI uses a feed-back control loop to continuously cope with the changes in channel load induced by factors like mobility. TPC PI only uses local information to sense the level of channel load and to adjust transmit powers in order to relieve it in case the level is too
6. CONCLUSIONS AND RECOMMENDATIONS FOR FURTHER RESEARCH

This approach applies real-time corrections in an attempt to establish load stability for the purpose of enhanced PDRs. In the case of TPC CLS we use information related to a given vehicle's neighbors to execute more or less drastic actions for channel load control. With TPC CLS every vehicle is meant to determine its own share of contribution to the total channel load sensed by it. For both approaches we observe that for scenarios without randomized mobility the PDR is significantly improved in comparison to IEEE 802.11p and ETSI DCC for TX-RX distances up to 100 m. In particular, TPC CLS shows an improvement in PDR values in comparison with TPC PI. However, for scenarios with mobility and random inter-vehicle distances the benefits of both approaches were diminished and at a certain point the attained performance is similar to that of simple IEEE 802.11p and ETSI DCC.

Moreover, given the fact that both TPC PI and TPC CLS are based on PI controllers, they also suffer the limitations of that kind of solutions. In control theory, a target system is most of the times unique and therefore the control loop is also tuned uniquely. In this research underlying this thesis, we have used a manual approach to tune the parameters of our PI control loop to obtain an acceptable performance in terms of PDR. Such tuning only applies to the set of vehicles and the network's parameters that we choose for our experiments. This means that our PI control loop works only for the analyzed network scenario. Therefore, in case of changes on the network characteristics a re-tuning may be necessary as we explain in the next section. In particular, this observation applies to changes in the propagation effects between transmitter and receiver, which are obviously out of control of the TPC algorithms.

Despite the advances in the congestion control of vehicular wireless channels, there are still several challenges to tackle. Our TPC CLS approach proved to be efficient in several cases and scenarios but it still takes local information on its channel load share based on the number of detected neighbors. In this thesis work we decided to choose information of the vehicles' neighborhood to improve the performance of the network. Despite the results and the improvement of ETSI DCC performance results, we think that the share of information among vehicles in a vehicular network is beneficial but in our case is shown to be not enough to assure high performance for the more realistic scenarios. However, We also think that information share leads to a tradeoff between how much information is useful to improve performance and how much overhead is added to the communication channels by sharing certain amount of information.

6.2. Recommendations for further research

The benefit of improving the performance of this kind of networks will become even more evident in the upcoming years because vehicular networks will tackle problems like road accidents and inefficient traffic. Some of the benefits of tackling such problems are human lives safety, climate change relief and time/resources optimization. Already in our time we hear about our nations' concerns and efforts to stop climate change. On this scenario vehicular networks can be a way to achieve that goal if vehicles' emissions are reduced based on the control and optimization of vehicular traffic.

Our work shows the benefit of using information from neighbors in order to decide whether or not a station puts a too-high load on the channel. At the present time, the only information used is the number of direct neighbors and their actual induced (measured) channel load. Improvements can be expected if this information becomes more refined, e.g. by disseminating the transmit power as well, and by the availability of received signal strengths. With the availability of this additional information, a more precise assessment can be made about the individual "load share" of vehicles in the neighborhood.

Exchanging this additional information comes at a price: we have to extend the current protocols in order to facilitate the information exchange. A study of the trade-offs between the additional load generated by the information exchange and the marginal benefits it yields is also recommended. Regarding the PI control loop that we use as an alternative for channel load control, research towards the self-optimization of that loop is also an interesting path for research. A self-optimized control loop can add adaptability on rapidly changing vehicular scenarios. Another recommendation for research can be focused on the optimization of TX rate control or inter-message times via the PI control loop or in combination with the TX power control proposed by this thesis work. Further investigation for TPC PI and TPC CLS on different vehicular topologies and road infrastructure is also recommended.
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