Programa de Doctorado en Tecnologías Industriales y de Telecomunicación

Cooperative Perception for Connected and Automated Vehicles using V2X Communications

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¡Alabado sea Dios!

அகர முதல எழுத்தெல்லாம் ஆதி
பகவன் முதற்றே உலகு.

All Praise to God

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Resumen

Los vehículos autónomos hacen uso de múltiples sensores para detectar su entorno. Los sensores utilizados (cámaras, radares o lidars) han mejorado significativamente su capacidad de detección en los últimos años. Sin embargo, sus capacidades aún están limitadas ante la presencia de obstáculos o condiciones climáticas adversas, entre otros factores. Una opción para mitigar estos retos es la percepción cooperativa o colectiva, la cual permite a los vehículos intercambiar información sobre los objetos detectados por sus sensores utilizando las comunicaciones V2X (Vehicle-to-Everything). De esta forma, los vehículos disponen de información no sólo de los objetos detectados por sus propios sensores sino también de los detectados por los sensores de los vehículos cercanos. De esta forma, la percepción cooperativa permite que los vehículos mejoren su rango de detección más allá de las capacidades de sus sensores locales. La percepción cooperativa también puede ayudar a mejorar la precisión y confianza en la detección de objetos, y ayuda a mitigar el impacto negativo de las condiciones climáticas o de visibilidad adversas.

ETSI y SAE están definiendo actualmente nuevos estándares V2X para la percepción cooperativa. SAE aún no ha publicado su estándar, mientras que ETSI ha publicado un Informe Técnico sobre percepción colectiva que incluye aspectos importantes como el formato del Mensaje de Percepción Colectiva (CPM) y las reglas de generación de mensajes para decidir cuándo debe generarse un nuevo CPM y qué información debe incluir. ETSI está actualmente en proceso de finalizar un primer estándar sobre percepción colectiva, y asociaciones industriales como el CAR 2 CAR Communication Consortium (C2C-CC) y 5G Automotive Association (5GAA) han incluido la percepción cooperativa en sus hojas de ruta. Todos estos esfuerzos destacan el interés industrial y el potencial de las comunicaciones V2X para apoyar el desarrollo y despliegue de la percepción cooperativa en vehículos conectados y autónomos. A pesar de los avances realizados hasta la fecha, el concepto de percepción cooperativa es relativamente novedoso y se requiere

un profundo estudio de su funcionamiento y rendimiento antes de considerar su despliegue comercial.

La percepción cooperativa permite intercambiar de forma frecuente actualizaciones sobre los objetos detectados por los sensores con el fin de aumentar la precisión de la detección. Sin embargo, las actualizaciones frecuentes aumentan la carga en los canales de comunicación, y suponen un reto para la escalabilidad de la red de comunicaciones V2X y la efectividad de la percepción cooperativa. Además, pueden generar altos niveles de redundancia pues muchos vehículos cercanos pueden detectar un mismo objeto y reportarlo simultáneamente. Este reporte simultáneo puede, hasta cierto punto, mejorar la precisión en la detección. Sin embargo, un alto nivel de redundancia puede sobrecargar el canal de comunicaciones y afectar al funcionamiento y efectividad de la percepción cooperativa ante la imposibilidad de transmitir los mensajes críticos por la saturación del canal de comunicaciones. El desafío general en la percepción cooperativa ocurre principalmente cuando el mensaje de la percepción cooperativa no está bien organizado. Por ejemplo, podría ser muy ineficiente generar un mensaje de percepción cooperativa que contenga una pequeña cantidad de objetos detectados, lo que también podría aumentar la carga del canal de comunicaciones y podría afectar la percepción cooperativa.

Esta tesis estudia y evalúa exhaustivamente el funcionamiento y rendimiento de la percepción cooperativa, y propone diferentes soluciones para mejorar su eficiencia y escalabilidad. Para ello, en primer lugar, la tesis realiza un estudio de dimensionado para comprender mejor el funcionamiento de la percepción cooperativa, e identificar las posibles ineficiencias existentes. Este estudio evalúa las reglas de generación de mensajes de percepción cooperativa propuestas en ETSI, y analiza en detalle el impacto de diferentes configuraciones de sensores, densidades de tráfico y tasas de penetración de la tecnología en el mercado. Esta tesis también investiga por primera vez el impacto del control de congestión en la percepción cooperativa. Este estudio es muy relevante ya que los protocolos de control de congestión pueden modificar la generación y transmisión de mensajes cuando el canal radio está congestionado, y por lo tanto alterar el funcionamiento de la percepción cooperativa. El estudio considera el sistema de control de congestión (DCC, control de congestión descentralizado) estandarizado por ETSI y que abarca varias capas de la pila de protocolos. El estudio realizado demuestra el impacto de la configuración DCC en el funcionamiento y efectividad de la percepción cooperativa.

En base a los resultados del estudio de dimensionado, esta tesis proponen dos técnicas para mitigar las ineficiencias identificadas en el proceso de percepción cooperativa, la técnica Look-Ahead y una técnica de mitigación o control de redundancia. La técnica de mitigación de redundancia reduce la redundancia en la red de comunicaciones eliminando del mensaje de percepción cooperativa los objetos detectados que no han cambiado significativamente su posición, velocidad y rumbo desde la última vez que fueron recibidos como parte de un mensaje de percepción cooperativa enviado por otro vehículo cercano. La evaluación muestra que la técnica de control de redundancia propuesta reduce significativamente la redundancia y la carga del canal de comunicaciones, y mantiene la capacidad de percepción para distancias cortas y medias críticas para la seguridad. La técnica Look-Ahead reorganiza la transmisión de objetos en el mensaje de percepción cooperativa con el fin de reducir el overhead en las comunicaciones V2X. Para ello, la técnica incluye objetos en el mensaje de percepción cooperativa actual que predice se incluirían en el siguiente mensaje de percepción cooperativa. Esta reorganización busca reducir el número de mensajes de percepción cooperativa generados haciendo que cada mensaje incluya información sobre una mayor cantidad de objetos detectados. Los resultados del análisis muestran que Look-Ahead reduce el overhead y la carga del canal de comunicaciones V2X a la vez que mejora la percepción de los vehículos. Por último, la tesis propone métodos para combinar las técnicas propuestas (Look-Ahead y mitigación de redundancia) con el fin de mejorar aún más la efectividad de la percepción cooperativa y la escalabilidad del sistema. Este estudio considera la combinación de las dos técnicas con y sin control de congestión DCC, y muestra que las combinaciones propuestas reducen la carga del canal y mejoran la escalabilidad de los servicios de percepción cooperativa.

Abstract

Automated vehicles make use of multiple sensors to detect their surroundings. The sensing technology has significantly improved over the last years. However, the capabilities of on-board sensors like cameras, radars, or lidars are still limited under the presence of obstacles or adverse weather conditions, among other factors. Cooperative perception (a.k.a. collective perception or cooperative sensing) has been proposed to help mitigate these challenges by exchanging sensor data among vehicles using V2X (Vehicle-to-Everything) communications. V2X communications allow vehicles to exchange information about detected objects, and hence improve their sensing range beyond the capabilities of their local sensors thanks to cooperative perception. Cooperative perception can also help improve the vehicles' sensor detection accuracy and increase the confidence about the detected objects. It can also help mitigate the negative impact of adverse weather conditions or the negative effect of lighting conditions on the sensitivity.

ETSI and SAE are currently defining new V2X standards for cooperative perception. SAE has not yet published its standard. On the other hand, ETSI has published a Technical Report on collective perception that includes important aspects such as the Collective Perception Message (CPM) format and the message generation rules to decide when a new CPM should be generated and what information it should include. ETSI is now finalizing the standardization of the Technical Specification on collective perception. Industrial associations such as the C2C-CC and the 5GAA have included cooperative perception in their roadmaps. All these efforts highlight the industrial interest and potential of V2X communications to support the development and deployment of cooperative perception in connected and automated vehicles. Despite the advances made to date, the concept of cooperative perception is relatively new and an in-depth study of its operation and performance is required before considering its commercial deployment.

Cooperative perception allows frequent exchange of updates on the sensors detected objects to increase detection accuracy. However, the frequent updates increase the

channel load on the communications channels, and pose a challenge for the scalability of the V2X communications network and the effectiveness of cooperative perception. In addition, they can generate high levels of object redundancy since many nearby vehicles can detect the same object and report it simultaneously. This simultaneous reporting of objects can improve detection accuracy to some extent. However, a high level of redundancy can overload the communications channel and affect the operation and effectiveness of the cooperative perception given the impossibility of transmitting critical messages due to the saturation of the communications channel. The general challenge in cooperative perception occurs mainly when the cooperative perception message is not well organized. It might be very inefficient to generate a cooperative perception message that contains a small number of detected objects, which could also increase the load on the communications channel and affect cooperative perception.

This thesis extensively studies and evaluates the performance and operation of cooperative perception solutions and proposes different techniques to address the identified challenges, fulfilling the existing literature gaps. To this aim, the thesis presents first a dimensioning study to identify any inefficiencies in existing cooperative perception solutions and support the design of more advanced and scalable techniques. This dimensioning study evaluates the cooperative perception message generation rules proposed at ETSI and compares them with periodic generation policies to analyze its effectiveness and identify existing limitations. Then the impact of different sensor configurations, traffic densities and market penetration rates are analyzed in detail. The study also investigates the impact of congestion control on cooperative perception, since congestion control protocols can modify message generation and transmission when the radio channel is congested. ETSI has standardized a DCC (Decentralized Congestion Control) framework for V2X communications that spans over multiple layers of the protocol stack. To the author’s knowledge, this is the first study that evaluates the combination of the ETSI defined DCC Access and DCC Facilities on cooperative perception. The study demonstrates the importance of the DCC configuration for the operation of the V2X network and the effectiveness of cooperative perception.

Based on the findings of the dimensioning study, different techniques are proposed in this thesis to mitigate the inefficiencies identified. This thesis mainly proposes two different techniques, namely the look-ahead technique and redundancy mitigation or control technique. The redundancy mitigation proposal is designed to reduce the redundancy in the network by filtering the detected objects reported in cooperative perception messages that have not significantly changed their position, speed, and heading since the last time they were received as part of a cooperative perception message from other vehicles. The evaluation shows that the proposed redundancy mitigation technique significantly reduces the redundancy and channel load without degrading the perception for safety-critical short and medium distances. The Look-Ahead proposal reorganizes the transmission of objects in the cooperative perception message. It includes objects in the current cooperative perception message that are predicted to be included in the following cooperative perception message. This reorganization results in vehicles transmitting fewer messages, and each message includes information about a higher number of detected objects. This approach reduces the communications overhead and the channel load, and improves the perception. Finally, the thesis proposes methods to combine the proposed techniques (Look-Ahead and redundancy mitigation) to further improve the effectiveness of cooperative perception and the system's scalability. The different combinations are evaluated with and without DCC, and the conducted study shows that combining the two proposals can further reduce the channel load and improve the scalability of cooperative perception services without degrading the perception.

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List of Acronyms

3GPP	Third Generation Partnership Project
5GAA	5G Automotive Association
BSMs	Basic Safety Messages
BTP	Basic Transport Protocol
C2C-CC	CAR 2 CAR Communication Consortium
CA	Cooperative Awareness
CAMs	Cooperative Awareness Messages
CAVs	Connected and Automated Vehicles
CBR	Channel Busy Ratio
CPS	Collective Perception Service
CPM	Collective Perception Message
CSMA/CA	Carrier Sense Multiple Access with Collision Avoidance
DBU	Distance Between Updates
DCC	Decentralized Congestion Control
DCC_ACC	DCC Access
DCC_FAC	DCC Facilities
DIFS	Distributed InterFrame Space
DPs	DCC profiles
DEN	Decentralized Environmental Notification
DOR	Detected Object Redundancy
DSRC	Dedicated short-range communications
EDCA	Enhanced Distributed Channel Access
ETSI	European Telecommunications Standards Institute
FIFO	First-In-First-Out
FoV	Field of View
IA	Information Age

IEEE	Institute of Electrical and Electronics Engineers
ITS	Intelligent Transportation System
LA	Look-Ahead
LDM	Local Dynamic Map
LOS	Line-of-Sight
MAC	Medium Access Control
MCO	Multi Channel Operation
MPR	Market Penetration Rate
NLOS	Non-line-of-sight
OFDM	Orthogonal Frequency Division Multiplexing
OPR	Object Perception Ratio
PDF	Probability Density Function
PDR	Packet Delivery Ratio
PDU	Protocol Data Unit
RM	Redundancy Mitigation
RSU	Road Side Unit
SAE	Society of Automotive Engineers
SUMO	Simulation of Urban MObility
QoS	Quality of Service
TBU	Time Between Updates
V2V	Vehicle-to-Vehicle
V2X	Vehicle-to-Everything

1 Introduction

Automated vehicles use embedded sensors to drive autonomously with low or no human intervention. To this aim, the vehicle's planning system uses perception and localization data to determine the travel path and driving actions (e.g., lane changes, acceleration or braking) that are executed by the vehicle's control platform. For perception and localization, automated vehicles equip multiple exteroceptive sensors (e.g., lidars, radars, and cameras) that locally perceive the driving environment [1][2]. This environment includes the static elements (e.g., road shape and curvature, lane marks and trees) and dynamic moving objects (e.g., other vehicles, bicycles, pedestrians).

Sensors for automated vehicles have significantly improved their perception range and detection accuracy in the recent years [3]. However, the capabilities of these sensors can still be impaired due to the adverse weather conditions or sensitivity to lighting conditions, presence of obstacles in front of the sensors or other factors [4]. These limitations can negatively influence the safety and efficiency of the automated vehicles. V2X (Vehicle-to-Everything) communications can reduce this negative impact and improve the perception or sensing capabilities of the Connected and Automated Vehicles (CAVs) by facilitating the exchange of sensor data among the vehicles. This process is generally referred to as cooperative perception, collective perception or cooperative sensing [5][6]. Cooperative perception is the exchange of information about the driving environment using V2X communications. It enables vehicles to complement the information obtained with their on-board sensors with information obtained by the sensors of nearby vehicles. Cooperative perception therefore enables vehicles to receive additional sensor data about the driving environment, including data beyond their on-board sensors' field of view (FoV). By facilitating the exchange of sensor data among the vehicles, cooperative perception helps improve the vehicles' sensor detection accuracy and increases the confidence about the detected objects. This is because vehicles can correlate and compare the information from their on-board sensors with sensor information gathered from nearby vehicles using V2X communications. The exchange of sensor information also mitigates the negative impact of adverse weather conditions or the negative effect of lighting conditions on the sensor sensitivity. Cooperative perception also helps to detect vehicles or objects that were not detected by their onboard sensors. Figure 1 shows an example scenario of how cooperative perception can support CAVs at intersections when sensor detection is affected by the non-line-of-sight. As shown in the figure, the white vehicle is approaching the intersection to turn right. The white vehicle cannot detect the pedestrians because its on-board sensors are obstructed due to the presence of buildings, and therefore there is a safety risk. Cooperative perception can mitigate this risk thanks to the exchange of sensor information, because the red vehicle can detect the pedestrian with its sensor, and can use V2X to transmit their position to the white vehicle. Thanks to cooperative perception, the white vehicle can have the perception of the red vehicle which enables the white vehicle to extend its sensor FoV and helps to detect the pedestrians well in advance to take precautionary measures. This sharing of sensor information using cooperative perception will significantly improve the overall safety in the driving environment.

Figure 1. Cooperative perception at intersections

To understand the different functionalities involved in cooperative perception, the basic architecture for cooperative perception is presented in Figure 2. The on-board sensors locally perceive the environment and perform the necessary processing, fusion and detection tasks to support the automated driving functions. The information gathered by the sensors is also used as an input for the cooperative perception component. This component selects the information to be exchanged among vehicles and defines the message format. For example, it decides which detected objects should be included in a cooperative perception message and how often these messages should be transmitted. Congestion control protocols may adapt the rate at which the cooperative perception messages are generated and transmitted to control the communications channel load. It should be noted that the received cooperative perception messages are fused with the information obtained from the on-board sensors to improve and extend the vehicles' perception of the driving environment [2].

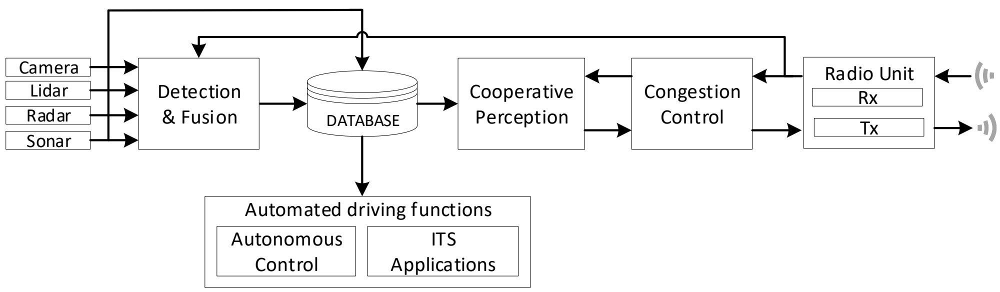


Figure 2. Basic architecture of cooperative perception

Cooperative perception relies on V2X communications for vehicles to exchange sensor data. The development of V2X communications was initially focused on the so-called Day One Services [7]. These services include, among others, a basic cooperative awareness service where vehicles regularly broadcast their position, speed and basic status information through CAMs (Cooperative Awareness Messages) based on ETSI (European Telecommunications Standards Institute) standards [8] or BSMs (Basic Safety Messages) based on SAE (Society of Automotive Engineers) standards [9]. This basic cooperative awareness service improves the awareness of vehicles, but the information exchanged is limited and does not exploit the rich sensor data gathered by CAVs.

ETSI [5] and SAE [6] are defining new V2X standards for cooperative perception. SAE has not yet published its standard for cooperative perception [6]. On the other hand, ETSI published a Technical Report on collective perception in December 2019 [5] and is currently working on the following Technical Specification [10]. In its Technical Report [5], ETSI defined the so-called Collective Perception Service (CPS). The CPS includes important functionalities such as the Collective Perception Message (CPM) format and the message generation rules to decide when a new CPM should be generated and what information it should include. In recent years, industrial associations such as the C2C-CC (CAR 2 CAR Communication Consortium) and the 5GAA (5G Automotive Association) have included cooperative perception in their roadmaps. Many research projects have adapted the concept of cooperative perception to improve vehicle safety in their driving environment [11][12]. These efforts highlight the industrial interest and potential of V2X communications to support the development and commercial deployment of cooperative perception in CAVs. However, before the commercial deployment, the concept of cooperative perception needs to be studied in detail since it is relatively new, in order to understand its operation, optimize it and analyze its impact on the V2X network.

At the beginning of this thesis, the research on cooperative perception was in its early stages and there was no dimensioning study performed on cooperative perception that analyzes its operation and performance. The objective of performing a dimensioning study is to evaluate the operation and performance of cooperative perception and understand the importance of different functionalities and the configurations involved in it. This dimensioning study will also help to identify the existing limitations in cooperative perception.

In this thesis, a detailed dimensioning study is conducted, evaluating the functioning of cooperative perception. The dimensioning study evaluates the cooperative perception message generation rules proposed in ETSI and shows that the detected objects are frequently exchanged to increase detection accuracy. However, the analysis identifies two main inefficiencies. The first one is related to the generation of high levels of redundancy since many nearby vehicles report the same object simultaneously. The second one is related to the fact that the generated cooperative perception messages are not well organized as the message generation rules generate frequent cooperative sensing messages that contains a small number of sensed objects. These inefficiencies should be addressed because it could overload the communications channel and affect the operation and effectiveness of the cooperative perception. The dimensioning study also analyzed in detail the impact of different sensor configurations, traffic densities, market penetration rates on the operation and performance of cooperative perception and shows that cooperative perception can significantly increase the communication channel load and activate the operation of congestion control protocols. This thesis then investigates for the first time the impact of congestion control on cooperative perception. This study is very relevant since congestion control protocols can modify the generation and transmission of messages when the radio channel is congested, and therefore alter the operation of cooperative perception. The study considers the congestion control system (DCC, decentralized congestion control) standardized by ETSI and covering several layers of the protocol stack. The study carried out demonstrates the impact of the DCC configuration on the functioning and effectiveness of cooperative perception.

The thesis further goes beyond the state-of-the-art and presents two proposals for cooperative perception that have then been developed to address the identified inefficiencies in the dimensioning study. First, a redundancy mitigation or control technique is proposed that significantly reduces the redundancy and the channel load in the network while maintaining the perception for safety-critical short and medium distances. The thesis then proposes the look-ahead technique that reorganizes the cooperative perception messages and reduces the communications overhead. The results show that the look-ahead technique improves the reliability of V2X communications and the perception of CAVs. Finally, the thesis proposes different methods to combine the redundancy mitigation and look-ahead techniques to further improve the overall effectiveness and scalability of the cooperative perception service.

1.1 Objectives

The primary purpose of this thesis is to investigate and improve the efficiency and scalability of cooperative perception. This goal is achieved in this thesis through several objectives which are listed and presented in this section.

Objective I: This thesis first aims to extensively review the existing cooperative perception solutions and standards in the literature, and identify any existing gaps. To this aim, the existing state-of-the-art has been extensively reviewed in this thesis and the evolution of the cooperative perception in the ETSI standardization process has been constantly monitored.

Objective II: Next, the thesis aims to develop a simulation platform for studying cooperative perception. At the time of starting the thesis, there were no open-source platforms for the evaluation of cooperative perception solutions that can provide an accurate modelling of the radio access technology, the different layers of the V2X communication protocol stack (including congestion control), an adequate radio propagation model, the sensing capabilities of the vehicles and the realistic road traffic models. Consequently, the author had to build its own simulator over an existing wireless simulation platform, and implemented the previously mentioned components into the simulator to evaluate cooperative perception.

Objective III: The thesis then aims to perform a dimensioning study to understand in detail the operation and performance of cooperative perception. The goal is to quantify the effectiveness of the existing cooperative perception message generation rules and identify any existing potential inefficiencies. The objective is also to understand how factors such as the market penetration rate (i.e. how many vehicles are automated and use V2X communications), the traffic density or the sensor configuration influence the performance and efficiency of cooperative perception.

Objective IV: The thesis then analyzes the impact of congestion control protocols on cooperative perception. The objective of this analysis is to understand how congestion control protocols impact the operation of cooperative perception because it modifies the generation and transmission of cooperative perception messages. The study also helps to understand the importance of the congestion control protocol configurations to achieve high effectiveness in the V2X network and in cooperative perception.

Objective V: Cooperative perception can be subject to significant redundancy levels since each object can be detected and transmitted by multiple vehicles nearly at the same time. The unnecessary transmission of excessive redundancy can limit the scalability of the V2X network, degrading the performance of cooperative perception and possibly other services that could be running on the same channel. This thesis seeks to first understand the level of redundancy generated by current cooperative perception solutions, and propose redundancy mitigation mechanisms that will help control the redundancy and improve the performance of cooperative perception.

Objective VI: Another objective of the thesis is to improve the effectiveness of cooperative perception by improving the generation of cooperative perception messages. The transmission of detected objects in cooperative perception messages can be highly inefficient if they are not adequately organized. Cooperative perception messages have a significant overhead produced by message and protocol headers, and therefore their transmission can be highly inefficient if they contain a small number of objects. Solutions will be proposed to mitigate this inefficiency.

Objective VII: The overall objective of this thesis is to improve the effectiveness and scalability of cooperative perception. To this aim, the thesis will then ultimately design and evaluate methods that combine all solutions proposed as part of objectives *IV* and *V*. Solutions will be designed and evaluated with and without congestion control mechanisms, and with the coexistence of cooperative perception messages and awareness messages.

1.2 Thesis structure and outline

The thesis is written by a compendium of published articles produced by the author of this thesis. The published papers are included in Annex A (from Annex A.1 to A.5). The studies published in these papers represent the core of the thesis. In addition, three initial chapters are included in this thesis to review the existing state-of-the-art, introduce important functionalities that support the successful deployment of cooperative perception, and present the simulation environment implemented and used in this thesis.

1.2.1 Outline

The outline of the thesis is organized as follows. Chapter 2 presents the current state-of-the-art in cooperative perception. This chapter initially presents the existing sensor technologies (e.g., lidar, radar and cameras) and discusses their challenges and limitations. The concept of cooperative perception is then introduced and its potential for mitigating sensor limitations is highlighted. This chapter then proceeds to discuss the main factors that can impact the effectiveness of cooperative perception (e.g., message format, rate, size and content) and reviews existing studies in the literature. In addition, the concept of ETSI DCC (Decentralized Congestion Control) is summarized, and studies analyzing the impact of DCC on cooperative perception are presented. From the analysis performed in the state-of-the-art, this chapter identifies the limitations and challenges of cooperative perception and missing gaps existing in the literature. A summary of the main conclusions and findings obtained is presented at the end of the chapter.

Chapter 3 presents the ITS (Intelligent Transportation System) communications architecture defined by ETSI to support V2X services and its different layers. Next, the IEEE 802.11p/ITS-G5 Access technology is presented since it is the technology used in the evaluations performed in this thesis. Furthermore, the DCC framework defined by ETSI to control congestion is presented. The DCC Access and DCC Facilities are explained in detail because they control the transmission and generation of V2X messages. Finally, the CPS being defined by ETSI is presented, with a focus on the Collective Perception Message format and the CPM generation rules.

Chapter 4 presents the simulation platform implemented and utilized in this thesis, in particular the new components implemented to simulate cooperative perception in vehicular networks. To obtain valid conclusions and insights, it is important to accurately model and simulate the vehicular network and the cooperative perception process. This chapter also explains the scenarios and the main simulation and communication parameters considered throughout the thesis. Finally, the performance metrics used in the thesis are explained in detail.

Chapter 5 presents a dimensioning study that analyzes the functionalities of the cooperative perception using V2X communications. In this context, the study quantifies the performance and effectiveness of cooperative perception using V2X communications, comparing ETSI message generation rules (that will be referred to as baseline generation rules) with periodic generation policies. This analysis shows that the baseline generation rules achieve an interesting balance between perception capabilities and communications performance when compared with periodic ones. However, the results obtained demonstrate that the baseline generation rules present certain inefficiencies that limit their scalability. The first inefficiency is related to the fact that the current baseline generation rules can generate a high number of CPMs with a small payload. This negatively impacts how efficiently the communications channel is utilized since the size of the CPM headers can increase the overhead. The second inefficiency is the transmission of redundant information since multiple CAVs can detect the same object and report about it simultaneously. The transmission and reception of redundant information about the same object can unnecessarily overload the communications channel and increase the computing power needed to process the exchanged sensor information. Optimizing these inefficiencies further could improve the overall effectiveness and scalability of the cooperative perception. Then, the dimensioning analysis evaluates components and factors that have an impact on the performance of cooperative perception. The study also investigates the impact of congestion control on cooperative perception using the DCC framework defined by ETSI. To the author’s knowledge, this is the first study that evaluates the combination of DCC Access and DCC Facilities on cooperative perception, and shows the importance of the DCC configuration to achieve ultimate effectiveness in the V2X network and in cooperative perception.

In Chapter 6, a redundancy mitigation technique is proposed to reduce the generation of high object redundancy in cooperative perception. To this aim, the chapter first illustrates and quantifies the redundancy problem in detail. Then, a redundancy mitigation technique is proposed to reduce redundancy by omitting the detected objects from the cooperative perception message that have not significantly changed their position, speed and heading since the last time they were received as part of a cooperative perception message. The results show that the proposal significantly reduces the channel load while achieving similar perception levels for short and medium distances.

Another inefficiency in cooperative perception is addressed in Chapter 7. This chapter presents a cooperative perception mechanism, referred to as Look-Ahead (LA), designed to reduce the generation of cooperative perception messages that contains small number of objects and improve the transmission efficiency and reduce the overhead caused by headers. This chapter first illustrates and quantifies the problem in detail and then the Look-Ahead proposal is presented and evaluated. Look-Ahead complements and extends the baseline generation rules by grouping the detected objects into larger cooperative perception messages. The analysis conducted demonstrates that Look-Ahead can effectively reduce the rate at which cooperative perception messages are generated and increase their size, while reducing the channel load (and overhead) and improving the reliability of V2X communications and the perception of CAVs.

The mechanisms proposed in Chapter 6 and Chapter 7 can provide significant benefits in terms of improving the perception and reducing the channel load in the vehicular network. However, they have been designed and evaluated independently. In Chapter 8, different methods to combine Look-Ahead and redundancy mitigation are proposed and evaluated to improve cooperative perception and the system's scalability. The study has evaluated the effectiveness and scalability of the combined Look-Ahead and redundancy mitigation techniques with and without congestion control mechanisms and with the coexistence of cooperative perception messages and awareness messages. The conducted evaluation has demonstrated that the proposed combination techniques significantly improve the perception of CAVs and reduce the information age. In addition, the combination techniques improve the scalability of cooperative perception services.

Finally, Chapter 9 summarizes the main conclusions that can be extracted from this thesis and provides indications about possible future research directions.

1.3 Results of the thesis

This doctoral thesis has resulted in two journal publications and two conference publications which are presented in the annexes in this thesis and are listed below:

- G. Thandavarayan, M. Sepulcre, J. Gozalvez., “Analysis of Message Generation Rules for Collective Perception in Connected and Automated Driving”, Proc. IEEE Intelligent Vehicle Symposium (IV), Paris (France), pp. 134-139, 9-12, June 2019.
- G. Thandavarayan, M. Sepulcre and J. Gozalvez, “Redundancy Mitigation in Cooperative Perception for Connected and Automated Vehicles”, Proc. IEEE 91st Vehicular Technology Conference (VTC2020-Spring), pp. 1-5, June 2020.
- G. Thandavarayan, M. Sepulcre and J. Gozalvez, "Cooperative Perception for Connected and Automated Vehicles: Evaluation and Impact of Congestion Control," IEEE Access, vol. 8, pp. 197665-197683, October 2020.
- G. Thandavarayan, M. Sepulcre and J. Gozalvez, “Generation of Cooperative Perception Messages for Connected and Automated Vehicles”, IEEE Transactions on Vehicular Technology, vol. 69, no. 12, pp. 16336-16341, December 2020.

These publications have been referenced in more than 100 works (according to Google Scholar). Also, part of the thesis work has been presented by Professor Javier Gozálvez (co-supervisor of this PhD thesis) in the following keynote presentations “V2X Networks for Connected and Automated Driving” at the international IEEE Local Computer Networks (LCN) October 2019, “Towards a Multi-Technology V2X Ecosystem for Supporting Connected and Automated Driving” at the international IEEE Vehicular Networking Conference (VNC) December 2019, and by Miguel Sepulcre (co-supervisor of this PhD thesis) in the 1st IEEE International Workshop on Intelligent Connected and Autonomous Vehicles (ICAV 2021), held in conjunction with the 29th IEEE International Conference on Network Protocols (ICNP2021) in November 2021.

One additional journal paper is currently under review and its reference is provided below:

- G. Thandavarayan, M. Sepulcre, J. Gozalvez and Baldomero Coll-Perales, “Scalable Cooperative Perception for Connected and Automated Driving”, Journal of Network and Computer Applications, May 2022 (In Revision).

It is also worth highlighting that the conducted evaluations and the techniques proposed in this PhD have been regularly presented in the ETSI (European Telecommunications Standards Institute) Collective Perception Service standard meetings. Also, the main contributions from the thesis are also part in the ETSI Collective Perception Service Technical Report (TR 103 562) and Technical Specification (TS 103 324) documents.

- ETSI ITS, "Intelligent Transport System (ITS); Vehicular Communications; Basic Set of Applications; Analysis of the Collective Perception Service (CPS) ", ETSI TR 103 562 V2.1.1, December 2019.
- ETSI ITS, "Intelligent Transport System (ITS); Vehicular Communications; Basic Set of Applications; Specification of the Collective Perception Service", ETSI TS 103 324 V0.0.52 (draft), Dec 2022.

During the doctoral study, the author was also working and contributing to the European (H2020) project “TransAID-Transition Areas for Infrastructure-Assisted Driving” and part of the thesis work is published in this TransAID project deliverables.

The author also contributed to other works developed within the framework of the thesis that has been published in conferences and other journals. The tasks carried out in these publications are within the framework of this thesis but with different lines of research.

- M. Sepulcre, J. Gozalvez, G. Thandavarayan, B. Coll-Perales, J. Schindler, M. Rondinone, "On the Potential of V2X Message Compression for Vehicular Networks", *IEEE Access*, vol. 8, pp. 214254-214268, November 2020.
- J. Schindler, B. Coll-Perales, X. Zhang, M. Rondinone, G. Thandavarayan, "Infrastructure-Supported Cooperative Automated Driving in Transition Areas", *Proc. IEEE Vehicular Networking Conference (VNC 2020)*, 16-18 December 2020, Virtual Conference.
- B. Coll-Perales, G. Thandavarayan, M. Sepulcre and J. Gozalvez, "Context-based Broadcast Acknowledgement for Enhanced Reliability of Cooperative V2X Messages", *Proc. IEEE Forum on Integrated and Sustainable Transportation Systems (ISTS)*, Delf, The Netherlands, 3-5 November 2020.
- M. Sepulcre, J. Mira, G. Thandavarayan, J. Gozalvez, "Is Packet Dropping a Suitable Congestion Control Mechanism for Vehicular Networks?", *Proc. IEEE 91st Vehicular Technology Conference (VTC2020-Spring)*, Antwerp, Belgium, 25-28 May 2020.
- Correa, R. Alms, J. Gozalvez, M. Sepulcre, M. Rondinone, R. Blokpoel, L. Lücken, and G. Thandavarayan, "Infrastructure Support for Cooperative Maneuvers in Connected and Automated Driving", *Proc. IEEE Intelligent Vehicle Symposium*, Paris (France), June 2019.

2 State of the Art

Automated vehicles make use of multiple sensors to detect their surrounding environment. The sensors technology has significantly improved over the past years [3][12]-[14], and automated vehicles incorporates multiple types of sensors with advanced technology for perception. However, there are still relevant perception challenges that need to be solved [4][14]. For example, the hindrance and uncertainty persist with the sensor perception due to poor weather and lighting conditions. This is particularly the case for lidars and cameras. Lidar sensing can be restricted by high refraction and reflection caused by dense fog, smoke and rain [4]. Also, high sun angles may increase the noise level and their detection range depends on the reflectivity of the laser beams [3]. Cameras are very good for classifying objects and provide additional information such as color, texture, etc. [4]. However, cameras' performance degrades under adverse weather and lighting conditions. In addition, the object information such as velocity and distance cannot be directly measured but must be calculated [4]. Radars on the other hand perform better than lidars and cameras in poor weather conditions (rain, snow, fog, etc.) [4], and some radars can detect objects at 250m distance [15]. However, they provide lower resolution than lidars, and have a limited field of view [4]. Radars also suffer from multipath fading, which reduces the accuracy of the detected objects [4]. The perception of automated vehicles also needs to be improved in complex urban environments. This is especially the case due to the presence of occluding objects (e.g., other vehicles or buildings) that can limit the sensor's range [14]. Also, lidar, radar and cameras can only work under Line-of-Sight (LOS) conditions. All these challenges and constraints limit the perception capabilities of automated vehicles that exclusively rely on their on-board sensors, which can highly impact their safety and driving efficiency.

Cooperative perception effectively addresses the above-mentioned sensor perception limitations by enabling the vehicles to exchange information about objects detected by their sensors using V2X (Vehicle-to-Everything) communications. In this way, the vehicles have information not only on the objects detected by their own sensors but also on those detected by the sensors of nearby vehicles. This allows vehicles to improve their detection range beyond the capabilities of their local sensors and helps to improve the object detection accuracy and confidence, and help mitigate the negative impact of adverse weather or visibility conditions. Some studies have focused on exchanging raw sensor data [16][17] for cooperative perception. However, exchanging raw sensor data would require a high bandwidth that can compromise the system's scalability. Other formats such as layered cost maps [18] are also proposed to specify the sensor data in a grid-based representation. To accurately track objects using a grid-based representation, vehicles need a 3D representation of each layer. This could increase the system's complexity and increase the computational load. As a result, the majority of studies conducted to date on cooperative perception consider exchanging information about the dynamic status of the detected objects (e.g., their position, speed, size and type). Part of the existing studies focused on the definition of the message format for cooperative perception. Rauch *et al*. in [19] investigated the concept of sharing detected objects information in cooperative perception. In this study, the authors experimentally evaluated the transmission latency and range for different message sizes and rates through various field tests. Günther *et al*. in [20] proposed to transmit additional information about the transmitter (e.g., its position and speed) and its sensor capabilities (e.g., detection range and field of view) along with the object information. This extension allows the receiving vehicles to also understand the capabilities of the transmitting vehicles and better identify free-space and unknown areas. The study in [21] analyzed the potential benefits of including different additional information, such as correlation and higher order derivatives (e.g., the acceleration or yaw rate) of the detected objects on the fusion accuracy.

The information included in cooperative perception messages and the message generation rate needs to be carefully studied because an increase in the message size or rate could increase the channel load which could impact on the effectiveness of the cooperative perception. To this aim, some studies have focused on controlling the generation of cooperative perception messages. For example, the study in [22] evaluated if a cooperative perception message should be attached to existing basic awareness messages like CAM [8], or if it should be transmitted as a separate message. Integrating the cooperative perception information to a basic awareness message could improve the transmission efficiency due to a lower overhead. However, it would limit the flexibility of the transmission of cooperative perception information because basic awareness messages have specific generation rules that do not necessarily match the needs of cooperative perception. As a consequence, most of the conducted studies to date focus on the transmission of cooperative perception messages independent to other basic awareness messages like CAMs. Early studies in [1][23] evaluated the periodic transmission of cooperative perception messages. However, this has shown to be highly inefficient and unnecessarily generated a high channel load. In [24], the vehicles generate periodic cooperative perception message but high periodic transmission rates are set to the vehicles that detect the blind sensor area of the nearby vehicles. The results show that this approach disseminates useful sensor information about objects in the non-line-of-sight regions. Transmitting all objects with high periodic transmission rates could provide safety and reliability (vehicles do not need to wait for several cooperative perception messages to know the objects detected by a neighbor), but it might be inefficient because it increases the message size and the channel load in the network.

To solve the above-mentioned inefficiencies, some studies propose to dynamically control the objects included in each cooperative perception message. If only the necessary detected objects were included in each cooperative perception message, the message size could be reduced, decreasing the channel load and improving the successful delivery of messages. This is crucial to efficiently use the available bandwidth for scalability and, at the same time, obtain high perception levels. To this aim, the study in [25] proposed different object inclusion techniques based on the detected object position to dynamically adapt the message generation rate, length, and content to control the channel load. The study demonstrates that the tracking errors and mapping accuracy are improved when rate and length control mechanisms are applied together. Regarding the content control, the study also concludes that the detected objects that are located farther away from the sender but near the edge of the sensors' range should be prioritized. Alternatively, the authors in [26] propose message generation rules to include objects in the cooperative perception message based on their mobility or dynamics (e.g., object position, speed, acceleration and heading). These message generation rules are the most accepted ones in the research community because they control both the message generation rate and its size by deciding when a new cooperative perception message should be generated and what information it should include. In this context, the transmitter includes an object in a cooperative perception message if its speed, acceleration or heading has significantly changed compared to the last time it was included in a cooperative perception message. The message generation rules proposed in [26] have been adopted so far in the ETSI activities on collective perception [1][10]. The performance achieved with these message generation rules has been studied using analytical models for different radio access technologies in [27][28]. The analytical studies in [27] and [28] provide important insights about the perception that vehicles can achieve with these message generation rules. They evaluate the impact of the market penetration rate and traffic density on the environmental awareness and information age. The studies identify that, in some scenarios, reducing the rate at which objects are included in cooperative perception messages would be beneficial in reducing the channel load and interference.

With cooperative perception, multiple vehicles could detect and report about the same object, and transmit the same information. This would increase the object redundancy at the receiver. Receiving redundant information could improve the detection accuracy and combat potential packet losses. However, a high level of redundancy may overload the communications channel and could impact the effectiveness of cooperative perception. In addition, the redundant information increases the computing power necessary for each vehicle to process the received information. Few studies analyzed the impact of reducing the object redundancy in cooperative perception. For example, [29] proposed to include an object in a cooperative perception message depending on its value or utility for its neighboring vehicles to reduce the redundancy. The idea is to omit those objects that are not important for other vehicles. The accurate estimation of the value of each object in a distributed and dynamic environment is challenging, and the same authors partially address this challenge in [30] using deep reinforcement learning. The authors in [31] proposed a probabilistic selection scheme to decide which objects are included in a perception message and suppress redundant transmissions. The scheme allows vehicles to adjust the transmission probability of each detected object based on the position, vehicular density and road geometry information. The study in [32] evaluates different object filtering techniques and demonstrates that reducing or controlling redundancy can significantly improve the network-related performance metrics (e.g., channel load and packet error rate) without reducing the number of detected objects through perception messages and the time between updates about the detected objects. These studies show that reducing object redundancy could have positive effect on the cooperative perception.

Vehicular networks integrate congestion control algorithms to control the channel load and avoid channel congestion [33]. ETSI has defined a DCC framework that operates across multiple layers of the V2X communication protocol stack. In general, several studies have analyzed the performance of DCC. For example, [34] analyzed the DCC Reactive approach in detail, and demonstrated that the Reactive approach could trigger synchronization problems where vehicles tend to synchronize and transmit messages at the same time. Alternatively, the study in [35] analyzed the DCC Adaptive approach in different scenarios, and reported that the Adaptive approach performs well with the steady state traffic scenario configurations. However, very limited studies have analyzed the impact of DCC on cooperative perception. This is important because the high load that the CPM (and other services) [36] could generate in the network could activate the DCC to control the channel load by altering the generation and transmission of CPMs and other services. Since cooperative perception relies on the reliable exchange of cooperative perception messages, DCC could impact the effectiveness of cooperative perception. The initial study in [22] studied the impact of the DCC Reactive approach at the Access layer with different configurations of DCC Profiles (or DPs). The study demonstrates that DCC does impact the performance and operation of cooperative perception, and should hence be carefully configured. The DCC framework defined by ETSI offers different configuration options, including the possibility to use the Adaptive approach at the Access layer, and the usage of the DCC Facilities component to adapt the message generation rate (DCC Access only adapts the message transmission rate). Further investigations are therefore needed to study the impact and optimal configuration of DCC for cooperative perception.

We should note that most of the discussed studies were not available at the time of starting this PhD, and the knowledge on cooperative perception was limited at that time. Existing studies focused on the overall performance of cooperative perception, and not on the impact of the message generation rules. In this context, this thesis progressed the state-of-the-art first with a detailed dimensioning analysis to understand the operation and performance of cooperative perception and the impact of the message generation rules and congestion control. The dimensioning study was aligned with the status of the ETSI standardization work on cooperative perception [5] at the time the study was conducted, including the definition of the CPM format and the generation rules. The dimensioning study has been critical to identify inefficiencies generated by current message generation rules. Two proposals have then been developed to address these inefficiencies by controlling the amount of redundant data exchanged by vehicles and reorganizing the cooperative perception messages to reduce the communications overhead. In addition, the thesis proposes different methods to combine these two proposals to improve the effectiveness and scalability of the cooperative perception service. All these contributions are explained in detail from Chapter 5 to Chapter 8.

3 V2X Communications and Cooperative Perception

This chapter presents some of the main technologies that influence the deployment of cooperative perception in CAVs and that have been important for this PhD thesis. This includes the V2X communications architecture and its access technology, the cooperative perception service and the DCC framework. We should highlight that the work conducted in this thesis and the concepts presented in this chapter are aligned and compatible with the current V2X communications standards.

Section 3.1 explains first the ITS communications architecture and the different layers defined by ETSI that form the V2X communications protocol stack. Section 3.2 presents the IEEE 802.11p/ITS-G5 Access technology that is used in this thesis as it has been the de-facto C-ITS technology in Europe and the most matured and tested technology for the V2X communications. All evaluations performed in this thesis are conducted using the IEEE 802.11p/ETSI ITS-G5 radio access technology. Section 3.3 presents the DCC framework defined by ETSI, and explains the DCC Access and DCC Facilities in detail since they control the transmission and generation of V2X messages. Finally, the Section 3.4 presents the recent developments in cooperative perception, and explains in detail the collective perception service defined by ETSI [5]. This includes the CPM format and the CPM generation rules.

3.1 V2X Communication Architecture

Figure 3 shows the ETSI ITS Communications Architecture for V2X communications that includes the different layers of the protocol stack: Applications, Facilities, Transport & Network, Access, Management and Security. The Applications layer is developed to support multiple classes of applications that support the in-vehicle operations. These applications are mainly grouped into active road safety, traffic efficiency, value-added services and various other applications. Depending on the applications, the Application layer specifies requirements such as reliability, security, latency and other performance parameters. The Facilities layer supports Applications with a set of common functionalities that can be classified into Application Support, Information Support, Communication Support and Session Support. The Facilities layer supports different V2X message generation components such as CPS, CA (Cooperative Awareness) basic service, and DEN (Decentralized Environmental Notification) basic service among others. These services generate and decode V2X messages like CPMs, CAMs and DENMs respectively. Facilities layer manages the geographical position, location referencing, time stamping, data presentations (e.g., ASN.1) and addressing. It also provides access to the Local Dynamic Map (LDM) which is used to store and manage both the static lane-specific information (e.g., roads, traffic lights) and dynamic object information (e.g., vehicles, pedestrians). Facilities layer also supports services like DCC Facilities congestion control protocol that used to control the total amount of messages that a node can transmit per second when there is a high congestion load in the network. More details about this technology are provided in Section 3.3.

The Transport & Network layer specifies different protocols such as the GeoNetworking [37] or the IPv6. GeoNetworking is an ad-hoc routing protocol adapted by ITS-G5 that delivers packets using geographical positions. The Basic Transport Protocol (BTP) [38] is a connection-less transport service that provides end-to-end delivery services to the transmitted messages. BTP is responsible for multiplexing and de-multiplexing the V2X messages (e.g., CAM, CPM and among others.) and transmitting messages via the GeoNetworking protocol. It also enables the Facilities layer to directly access the services provided by the GeoNetworking protocol. Pre-existing TCP/UDP transport and IP networking protocols are also supported for certain type of data traffic, and IPv6 packets can be transmitted using GeoNetworking protocol by adapting the sublayer GN6.

As shown in Figure 3, ETSI ITS communication architecture supports different communication technologies at the Access layer. This includes the IEEE 802.11p/ETSI ITS-G5 radio access technology that is adopted, without loss of generality, for the studies performed in this thesis. More details about this technology are provided in Section 3.2. The Management layer is responsible for managing the operations performed at the different layers of the protocol stack. Finally, the security layer provides security, privacy and protection to the exchanged V2X information. In addition to the existing ITS communication architecture, ETSI is currently working on a second version of the architecture to include Multi Channel Operation (MCO). In this regard, ETSI has published a Technical Report [39] that specifies the functional and technical requirements of the MCO concept and extended the ITS communication architecture to include MCO; this work was recently published in the Technical Specifications [40]. The inclusion of MCO accommodates the growing (bandwidth) demands of the safety related cooperative applications that mainly rely on V2X communications to transmit their messages.

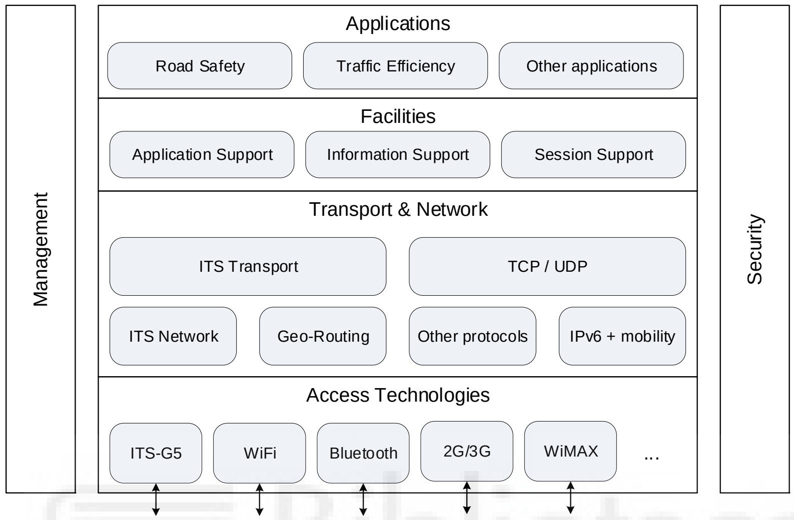


Figure 3. ETSI ITS Communications Architecture [41].

3.2 IEEE 802.11p/ETSI ITS-G5

Without loss of generality, the IEEE 802.11p/ETSI ITS-G5 radio access technology is considered in this thesis for the evaluation of the proposed solutions. IEEE 802.11p is an amendment of IEEE 802.11 [50] specifically designed for V2X communications. It has been adapted to the European context by ETSI in the ITS-G5 technology [51] and to the US in the DSRC technology [52]. IEEE 802.11p mainly features the PHY and MAC layers of the protocol stack to control the access of the radio channel.

At the PHY, IEEE 802.11p makes use of Orthogonal Frequency Division Multiplexing (OFDM) modulation with 52 subcarriers that are modulated using BPSK, QPSK, 16-QAM or 64-QAM. Convolutional coding is used for the forward error correction with a coding rate of 1/2, 2/3, or 3/4. The channel bandwidth is 10 MHz to reduce the impact on the multipath delay spread and Doppler effects caused by the high mobility vehicular environments. The modulation and coding schemes result in data rates between 3 Mbps and 27 Mbps. The default data rate defined by ETSI is 6 Mbps, although recent studies demonstrate that higher data rates can improve the system performance [53].

At the MAC, IEEE 802.11p operates in ad-hoc mode using Carrier Sense Multiple Access with Collision Avoidance (CSMA/CA). In CSMA/CA, a node having a packet to transmit must first listen to the radio channel to check whether another node is transmitting. If the channel is sensed as idle for a period higher than DIFS (Distributed InterFrame Space), then the node transmits. If the channel is sensed as busy due to other nodes' transmissions, the node must defer its transmission until the end of the ongoing transmission and wait for an additional random backoff time before starting the transmission. This backoff is used to minimize collisions between multiple nodes that also deferred their transmission since they also detected the channel as busy. The MAC layer is further improved with Enhanced Distributed Channel Access (EDCA) from IEEE 802.11e to support packet priority and Quality of Service (QoS). To this aim, four different priority queues are utilized to prioritize the packets based on its access category. Although CSMA/CA reduces packet collisions by adapting the backoff mechanism, it still suffers from hidden terminal problem. The hidden terminal problem occurs when two (or more) vehicles that are out of their carrier sensing range and cannot detect each other´s transmissions, transmit packets simultaneously causing a packet collision at the destination vehicle. As an example, in Figure 4, the transmission of vehicle A is not detected by vehicle B and vice versa, so both vehicles transmit a packet at the same time as they do not detect that the channel is busy. However, node C is in the transmission range of both vehicles and would simultaneously receive packets from A and B, thereby experiencing packet collision and a packet loss due to interference.

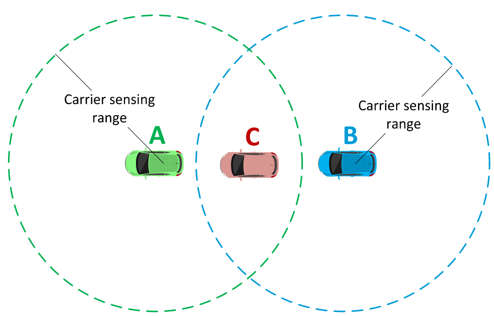


Figure 4. Hidden terminal problem in IEEE 802.11p.

3.3 Decentralized Congestion Control

Cooperative perception relies on the V2X exchange of information about the detected objects and its effectiveness depends on the correct reception of the exchanged V2X messages. The performance of V2X communications is highly influenced by the communication channel load since high channel load levels increase the risk of packet collisions. Vehicular networks integrate congestion control algorithms to control the channel load and avoid channel congestion [33]. These protocols can modify the packet generation and transmission rate or the power at which the messages are transmitted and even drop packets. Congestion control algorithms can then alter the generation and transmission of V2X messages and could then impact the effectiveness of cooperative perception [2].

ETSI has specified a DCC framework for V2X communications that spans over multiple layers of the protocol stack as shown in Figure 5. In particular, ETSI DCC has defined DCC_ACC, DCC_NET, DCC_FAC and DCC_CROSS components. The DCC_ACC [43] component is in the Access layer and operates as a gatekeeper to control the traffic that is effectively transmitted by each vehicle. DCC_NET [44] is optional and implemented at the Networking & Transport layer. It enables vehicles to exchange information about the channel load they sense so that each vehicle is aware of the channel load experienced by its one-hop and two-hop neighbors. The DCC_FAC [45] is currently defined as optional and is implemented at the facilities layer. For each vehicle, the DCC_FAC controls the number of messages generated by each application/service to proportionally distribute the channel resources. DCC_CROSS [46] defines the necessary management support functions for DCC and the required interface parameters between the DCC management entity and the DCC entities defined in the Facilities, the Networking & Transport and the Access layers. For all DCC components, the upper limits of the maximum transmission duration and the minimum time interval between two consecutive transmissions are defined in ETSI EN 302 571 [47].

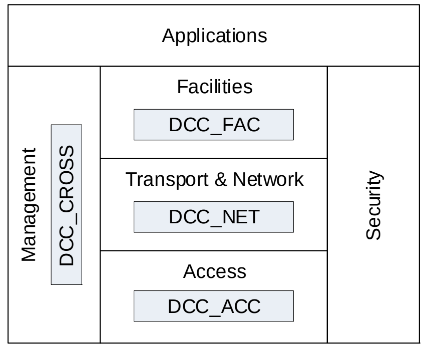


Figure 5. ETSI ITS Communications Architecture with DCC components

3.3.1 DCC Access

The DCC Access (DCC_ACC) [43] component is in the Access layer and acts as a gatekeeper to adapt the amount of time that each vehicle can access the channel as a function of the channel load. DCC Access can make use of prioritization, queuing and flow control to control the transmission rate of the different types of packets generated per vehicle. To this aim, prioritization classifies the generated packets according to their traffic class. Four different traffic classes are differentiated by DCC Access and the messages are mapped to four DCC profiles (DPs): DP0, DP1, DP2 and DP3, where DP0 has the highest priority. At the lower layers, these DCC profiles are mapped to the corresponding EDCA access categories of ITS-G5 [48]. Then queuing is applied with four different DCC queues to map the packets generated with each traffic class. Each DCC queue follows a first-in-first-out (FIFO) scheduling policy so that the packet that has been waiting longer in the queue is transmitted first. The DCC Access queuing mechanism drops those packets that have been waiting in the queue for a time longer than their lifetime. When a queue is full, no more packets are accepted. Finally, flow control is applied to de-queue packets from the DCC queues and send them to the lower layers for their radio transmission. Packets in higher priority queues are de-queued first. A packet in the low priority queue is only de-queued if there is no packet with a higher priority waiting in its corresponding queue. As a result, lower priority packets can suffer from starvation and never be transmitted [2].

DCC Access defines two potential approaches to control the packet rate transmitted per vehicle: Reactive and Adaptive. Both approaches adapt the time between consecutive packet transmissions based on the channel load or CBR (Channel Busy Ratio). The CBR is defined as the percentage of time that the channel is sensed as busy. However, the main difference between Reactive and Adaptive approaches relies on the flow control process. It is important to note that ETSI does not mandate the use of any approach, and the C2C-CC does not define a concrete algorithm in its Basic System Profile [49] to implement DCC. We evaluate these two approaches because they are widely used.

3.3.1.1 Reactive Approach

The Reactive approach performs flow control using a state machine [43]. As shown in Table 1, each state is mapped to a range of CBR values and the minimum time interval (T_{off}) allowed between message transmissions. T_{off} is the inverse of the maximum message transmission rate allowed per vehicle in each state as shown in the table. When the CBR changes, the Reactive approach switches to the corresponding state, changing the minimum T_{off} and maximum message rate allowed per vehicle. As a result, vehicles dynamically adapt their message rate based on the CBR.

Table 1. Mapping of CBR values to states and T_{off} for T_{on}< 0.5 ms [43].

State	CBR	Packet rate	T_{off}
Relaxed	< 30%	20 Hz	50 ms
Active 1	30% to 39%	10 Hz	100 ms
Active 2	40% to 49%	5 Hz	200 ms
Active 3	50% to 65%	4 Hz	250 ms
Restrictive	> 65%	1 Hz	1000 ms

3.3.1.2 Adaptive Approach

The Adaptive approach performs flow control using a linear control process. This approach is designed to adapt each vehicle packet transmission rate in order to converge the channel load to a target value CBR_{target}=68%. To this aim, each vehicle adapts every 200 ms the parameter δ that represents the maximum fraction of time that a vehicle is allowed to transmit. The parameter δ is updated based on the difference between the current CBR sensed and the target CBR using the following equation:

$$\delta = (1 - \alpha) \cdot \delta + \delta_{offset} \quad (1)$$

where

$$\delta_{offset} = \beta \cdot (CBR_{target} - CBR) \quad (2)$$

and

$$G_{max}^{-} \leq \delta_{offset} \leq G_{max}^{+} \quad (3)$$

The values of the parameters are defined in [43] as α=0.016, β=0.0012, G_{max}^{-}=-0.00025 and G_{max}^{+}=0.0005. The protocol computes then the time between packet transmissions

(T_{off}) after every transmission. To this aim, it considers the duration of the current packet (T_{on}) and the fact that 0.025s ≤ T_{off}≤1s:

$$T_{off} = \frac{T_{on}}{\delta} \tag{4}$$

3.3.2 DCC Facilities

DCC_FAC [45] is defined as optional and is implemented at the Facilities layer when considered. It controls the number of messages generated by each application/service within each vehicle. The control takes into account the messages' traffic classes or DCC profiles (DPs). Thus, DCC_FAC distributes access to the channel among the different applications/services within each vehicle. The standard does not specify any particular algorithm, but suggests one in the annexes [45], which has been adopted in this thesis. This algorithm currently supports ITS-G5 technology and future releases of DCC_FAC will incorporate other technologies such as LTE-V2X and 5G NR V2X, as well as MCO.

The DCC_FAC algorithm specified in the standard annexes makes use of the DCC Access limit, the message size and the message interval from each application/service and traffic class to proportionally distribute the channel resources. It is to be noted that distributing the channel resources with ITS-G5 is equivalent to distributing the channel access time. To perform this channel resources distribution, each vehicle first computes the average channel resources consumed by each application/service with index *j* and traffic class with index *i* based on the specific DCC Access algorithm adapted at the access layer.

For the Adaptive approach, the average channel resources consumed by each application/service with index *j* and traffic class with index *i* are estimated as:

$$\overline{CRE_{ij}} = \frac{\overline{T_{on\,ij}}}{\overline{\overline{T_{on\,ij}} + \overline{T_{off\,ij}}}} \tag{5}$$

For the Reactive approach, these resources are estimated as:

$$\overline{CRE_{ij}} = \frac{1}{\overline{\overline{T_{off\,ij}}}} \tag{6}$$

where the average message duration $\overline{T_{on\,ij}}$ and the average message interval $\overline{T_{off\,ij}}$ are computed from the last second. Equation (5) is defined in the standard, but we adapted equation (6) for the Reactive one because it uses only T_{off}, which is defined as the minimum time interval allowed between message transmissions. Using equation (5) or (6), the total channel resources CR_i from all applications/services of traffic class *i* can be calculated as:

$$CR_i = \sum_j \overline{CRE_{ij}} \quad (7)$$

The channel resources CBR_a is defined as the available CBR percentage per radio channel for a vehicle and this value represents the upper limit of the time fraction that the vehicle is allowed to transmit on the radio channel. For the Adaptive approach, $CBR_a = \delta$, i.e., the maximum fraction of time that a vehicle is allowed to transmit. However, for the Reactive approach, $CBR_a = 1/T_{off}$, i.e., the maximum number of messages that the vehicle can transmit per second. CBR_a is used by DCC Facilities as an input to distribute the available channel resources among the different traffic classes. The traffic class with the highest priority is TC_0, so the available channel resources for this traffic class ACR_0 is set equal to CBR_a. If traffic class TC_0 does not consume all the available channel resources for the vehicle, the remaining resources are assigned to the next traffic class. As a result, ACR_i for traffic class *i* is calculated as:

$$ACR_i = max(0, ACR_{i-1} - CR_{i-1}) \quad (8)$$

Equation (8) can be applied to both Reactive and Adaptive approaches at the DCC Access, but ACR_i represents a fraction of time for Adaptive and a message rate for Reactive since they use a different CBR_a. DCC Facilities then identifies the channel resources ACR_{ij} that each application/service *j* belonging to the same traffic class *i* can use. To this aim, it considers the average channel resources consumed by each application/service calculated with equation (5) for Adaptive and equation (6) for Reactive:

$$ACR_{ij} = \frac{\overline{CRE_{ij}}}{CR_i} \times ACR_i \quad (9)$$

For the Adaptive approach, the minimum interval $T_{off\,min\,ij}$ for each application/service with index *j* and traffic class with index *i* can be then calculated as follows:

$$T_{off\,min\,ij} = \overline{T_{on\,ij}} \times \frac{1 - ACR_{ij}}{ACR_{ij}} \quad (10)$$

For the Reactive approach, ACR_{ij} is a message rate and the minimum interval $T_{off\,min\,ij}$ can be directly computed as:

$$T_{off\,min\,ij} = \frac{1}{ACR_{ij}} \tag{11}$$

$T_{off\,min\,ij}$ is then used to adapt the minimum time interval between message generations of each application/service and traffic class. As a result, the time interval between consecutive messages of each application/service and traffic class is dynamically adapted to satisfy the DCC Access limits imposed to each vehicle [2].

3.4 Cooperative perception

Different standardization bodies such as ETSI [5] and SAE [6] are working on the definition of new V2X standards for cooperative perception. SAE has not yet published its standard but ETSI has defined a so-called Collective Perception Service standard and has already published the Technical Report (TR 103 562) [5] and the draft version of the Technical Specifications (TS 103 324) [10]. The published Collective Perception Service defines all the necessary functions and interfaces to implement cooperative perception using V2X communications. In particular, it includes the definition of the CPM format that includes the necessary message headers and different containers, the CPM generation rules to decide when a new CPM should be generated and what information it should include, and other main interfaces that support the deployment of cooperative perception. More details of the CPM format and the generation rules are further presented in the following subsections.

3.4.1 Collective Perception Message format

The CPM is a broadcast message that will use V2X communications to complement the capabilities of on-board sensors and improve their safety and driving. The CPM contains information about the sender vehicle or RSU (Road Side Unit), its on-board sensors configurations (e.g. their range, field of view, etc.), and the dynamics of the detected objects (e.g. its position, speed, size, etc). As shown in Figure 6, every generated CPM includes an ITS PDU (Protocol Data Unit) header and 5 types of containers: a Management Container, a Station Data Container, a Sensor Information Container, a Perceived Object Containers and a Free Space Addendum Container. In particular, the ITS PDU header [42] includes data elements such as the protocol version, the message

ID and the station ID. The Management Container is mandatory and contains basic information about the transmitter, including its type (e.g., vehicle or RSU) and position. The Station Data Container is optional and includes additional information about the originating vehicle or RSU. The Sensor Information Container is optional and describes the sensing capabilities of the transmitter. In particular, each Sensor Information Container includes data elements such as the sensor ID, sensor type (e.g., radar, lidar or a sensor fusion system) and its detection area. The Perceived Object Container is optional and describes the dynamic state and properties of the detected objects. In particular, each Perceived Object Container includes the:

- Object ID that identifies the object and can be used for tracking purposes;
- Time of measurement that provides the time difference between the message generation time and the object measurement time;
- IDs of the sensors that have detected the object;
- Position, speed, acceleration and size of the object (among other fields);
- Confidence associated to the object;
- Object type (vehicle, person, animal, other).

The Free Space Addendum Container is optional and describes the free space areas within the sensor detection areas. In addition, it includes their associated confidence levels. It is to be noted that each CPM can include up to a maximum of 128 individual containers from each Sensor Information Container, Perceived Object Container and Free Space Addendum Container.

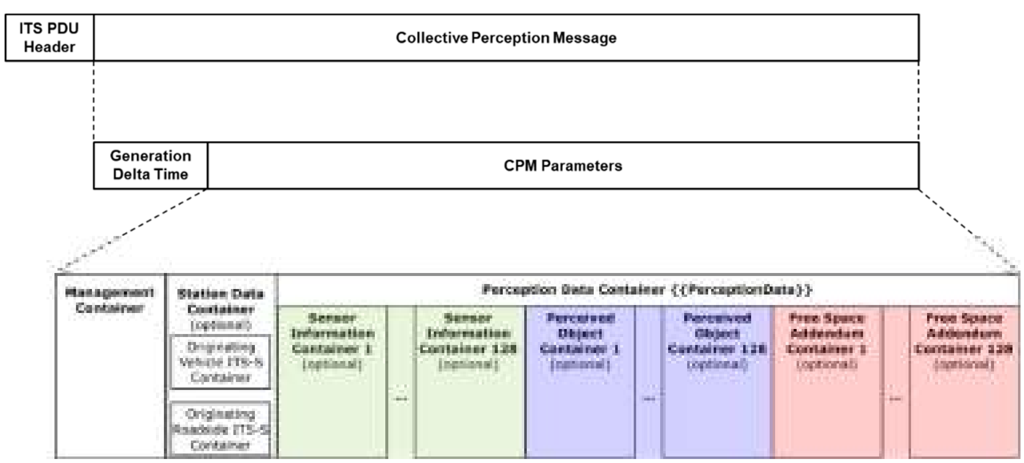


Figure 6. CPM format (adapted from [5]).

3.4.2 Collective Perception Message generation rules

The CPM generation rules define when a vehicle or RSU should generate and transmit a CPM and the information the CPM should include (e.g., which detected objects must be included). The CPM generation rules defined by ETSI in [5] will be used as a reference in this thesis and referred to as the baseline generation rules.

The baseline generation rules establish that a vehicle has to check every *T_GenCpm* if a new CPM should be generated. *T_GenCpm* should be set between 100 ms and 1000 ms, and can be adapted by DCC based on the channel load (see Section 3.3). For every *T_GenCpm*, a vehicle should generate a new CPM if it has detected a new object (i.e., an object that the vehicle has not transmitted before), or if any of the following conditions are satisfied for any of the previously detected objects:

1. The absolute difference (ΔP) between the current position of the object and its position the last time it was included in a CPM is higher than 4 m.
2. The absolute difference (ΔS) between the current speed of the object and its speed the last time it was included in a CPM is higher than 0.5 m/s.
3. The time difference (ΔT) between the current time and the last time the object was included in a CPM is higher than 1 s.

The vehicle includes in a new CPM all new detected objects and those objects that satisfy at least one of the previous defined conditions (i.e., ΔP>4m or ΔS>0.5m/s or ΔT>1s). A CPM is still generated every second even if none of the detected objects satisfy any of the previous conditions. The information about the on-board sensors are included in the CPM only once per second. The pseudo-code for the baseline generation rules is provided in Algorithm I.

ALGORITHM I. BASELINE GENERATION RULES
Input: Detected objects
Output: Objects (if any) to include in CPM
Execution: Every *T_GenCpm*

```
For every detected object do
    If the object is a new detected object then
        Include object in current CPM
    Else
        Calculate ΔP, ΔS and ΔT since the last time the object was included in a CPM
        If ΔP>4 m || ΔS>0.5 m/s || ΔT>1 s then
            Include object in current CPM
        End If
    End If
End For
```

4 Simulation Platform and Scenarios

Simulations are used in this PhD thesis to evaluate the performance of cooperative perception and the different proposals. Simulations provide the necessary flexibility and accuracy needed to evaluate large scale scenarios, and also present an adequate compromise between accuracy, scalability, and repeatability. In this context, the research to be carried-out on cooperative perception demands an accurate system-level simulation of the vehicular network. In particular, it demands an accurate modeling of the radio access technology, the different layers of the V2X communication protocol stack (including DCC) and an adequate radio propagation model. The vehicular network should support different market penetration rates and the connected vehicles in the scenario should be able to generate and transmit different V2X messages (e.g., CAM and CPM) following the standard definitions. Also, realistic road traffic modeling is required given the importance of the vehicular mobility (i.e., position and speed) for the detection of nearby vehicles using the on-board sensors. The sensing capabilities of each vehicle in the scenario should be carefully modeled to detect objects and should have the adaptability to incorporate multiple sensors with different range and field-of-view configurations. This chapter describes the simulation platform implemented and utilized. It also explains the traffic scenarios used and the main parameters considered, as well as the performance metrics used in this thesis.

4.1 Simulation platform

The research conducted is performed using the discrete event-driven network simulator ns3 and the road mobility simulator SUMO (Simulation of Urban MObility). The ns3 simulator is an open-source software implemented using the C++ programming language. The ns3 software is built with a different set of libraries that can be integrated together to simulate vehicular networks and provides flexibility to add new libraries or even extend the existing ones. In this thesis, ns3 is adapted to use the ITS-G5 [51] V2X standard based on IEEE 802.11p for simulating vehicular networks. The simulator is also expanded with additional libraries that include a collective perception service component following the ETSI specifications (Section 4.1.1), a sensing component to simulate different sensing capabilities of vehicles (Section 4.1.2), the ETSI DCC framework (Section 4.1.3) and a radio propagation component (Section 4.1.4). The capabilities and functionalities of each developed and integrated components are explained in detail in the following subsections.

For modeling the road traffic scenarios, the simulator SUMO is used. SUMO is an open source microscopic simulator that can handle large networks. It can generate continuous traffic and integrates a reliable car following model. Based on the scenario configurations (e.g. vehicle density, number of lanes, speed per lane), SUMO generates the vehicle mobility patterns that contain the detailed position information of every vehicle in the scenario. These vehicle mobility patterns are then extracted from SUMO as mobility trace information and exported into ns3 to generate the vehicle mobility in the simulation scenario.

4.1.1 CPS component

We have developed in this PhD thesis a CPS component in ns3 that strictly follows the CPM format and generation rules defined by ETSI (see Section 3.4). To this aim, each vehicle in the simulation scenario stores different information in its database. This includes, for example, the dynamic information (e.g., position, speed and heading) of its own and other detected vehicles. It also stores the on-board sensor configurations that need to be added in the CPM based on the applied generation rules. Using this information, the CPM component can implement baseline generation rules (see Section 3.4.2) and generate CPMs. When a CPM is generated using baseline generation rules, it includes all the necessary containers and their respective data fields in the CPM (see Section 3.4.1). This enables the vehicles to transmit CPMs with real dynamic information which can be received at the receiver vehicles for further processing. The CPS component also has the ability to dynamically compute the CPM size based on the number of mandatory and optional containers included in each CPM. The number of containers included in the CPM depends on the number of detected objects and on-board sensors. The developed CPS component can support large simulations and be easily imported to any version of ns3.

4.1.2 Sensing component

A sensing component has also been developed in ns3 within this PhD thesis to integrate the sensor capabilities for every vehicle in the scenario. With this component, each vehicle can have multiple sensors and each sensor can be configured with a different sensor range and field of view. The 2D sensor shadowing effect (sensor masking) is implemented in the XY-plane (shown in Figure 7) such that the sensors can detect only the vehicles that are in their Line-of-Sight (LOS); the occluded vehicles are not detected. When vehicles have multiple sensors, this component has the facility to enable or disable the sensor fusion in the scenario. For example, when sensor fusion is enabled and if several sensors in a vehicle detect the same object, their information is fused, and the object is reported only once in each generated CPM.

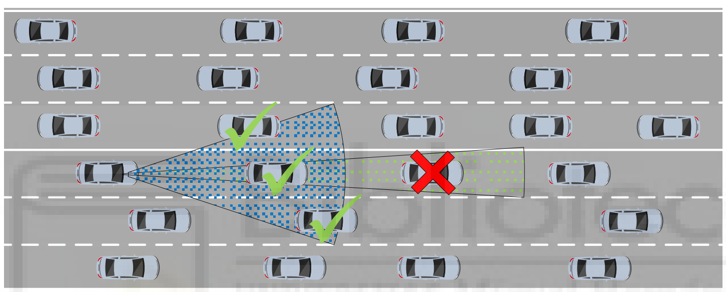


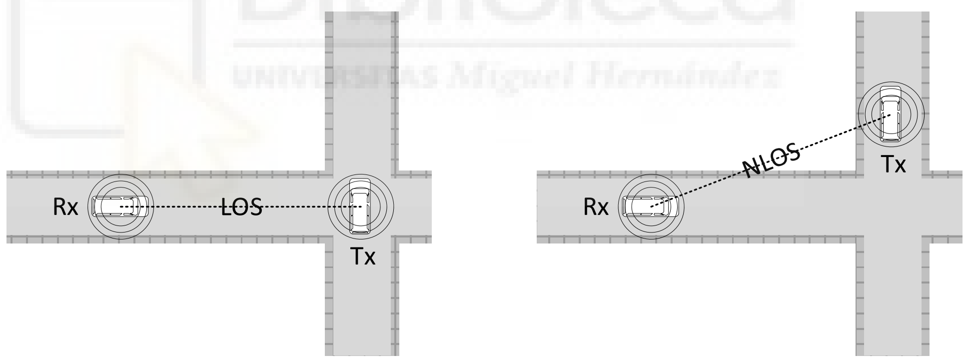
Figure 7. Sensor shadowing effect

4.1.3 DCC component

The DCC component developed in ns3 integrates the existing implementation of the DCC Access module that is publicly available in [54]. This is a plug-and-play module that can be easily integrated into ns3. The DCC Access module enables the vehicles in the scenario to select Reactive or Adaptive approach to control the channel load. This module allows controlling different parameters such as queue length, message lifetime in the queue or message priority (DCC profiles), among others, which provides high flexibility in evaluating the DCC Access. In this thesis, a DCC Facilities module has also been implemented for ns3 that follows the algorithm presented in Section 3.3.2. The DCC Facilities module dynamically adapts its equations based on the DCC Access approach enabled at the access layer to control the number of generated V2X messages. The DCC Facilities module support vehicles to generate different V2X message types (e.g., CAM and CPM) that can be configured with the same or different priorities. This provides more flexibility in analyzing the relevance and impact of several configurations in DCC.

4.1.4 Radio propagation component

The simulator ns3 has also been extended in this thesis with a radio propagation model for computing the path loss and shadowing effect. In particular, the Winner+ B1 propagation model has been implemented following the 3GPP recommendations (TR 36.885) for V2X simulations [55]. Winner+ B1 model uses a log-distance model for path loss and takes into account the propagation conditions between Line-of-sight (LOS) for the highway scenarios (see Figure 8a) and Non-line-of-sight (NLOS) for the urban scenario (see Figure 8b) for considering the strong impact of buildings on the V2X communications. The pathloss also considers the antenna height of 1.5m for both transmitting and receiving vehicles and when the distance between transmitter and receiver is less than 3m, the pathloss for 3m is computed. Finally, the computed path loss (especially useful for LOS conditions) is compared with the free-space path loss (i.e., line-of-sight path through free space) condition and the highest value is applied to the packet. The shadowing effect is modeled using a log-normal distribution with zero mean and a standard deviation of 3 dB for LOS and 4dB for NLOS is applied.



(a) Line-of-sight (LOS) (b) Non-line-of-sight (NLOS)

Figure 8. Propagation condition scenarios

4.2 Scenarios and parameters

4.2.1 Traffic scenarios

In this thesis, the simulations are conducted on a highway scenario with varying traffic densities. The highway scenario is created as a straight road segment with a length of 5 km and the vehicles travel on both directions as shown in Figure 9. Table 2 shows the different traffic densities selected for the highway scenario that corresponds to a service level C according to the Highway Capacity Manual [56], i.e., vehicles can drive at a speed close to the free flow speed but freedom to maneuver within the traffic stream is restricted. The low and medium traffic densities are configured with 3 lanes per driving direction and the high density with 4 lanes per driving direction. A higher traffic density has been considered in this study to analyze the scalability of cooperative perception in the vehicular network. For each traffic density, the speed for each lane has been selected based on the statistics of a typical 3-lane US highway obtained from the PeMS database [57]. Vehicles in the scenarios measure 5 m × 2 m. To avoid boundary effects, the statistics are only taken from the vehicles located in the 2 km around the center of the simulation scenario (see the blue square in Figure 9).

Table 2. Highway traffic scenarios

Parameter	**Traffic density scenarios**		
	Low	**Medium**	**High**
Number of lanes	6	6	8
Traffic density [veh/km]	60	120	240
Speed per lane [km/h]	140 132 118	70 66 59	50 km/h for all lanes

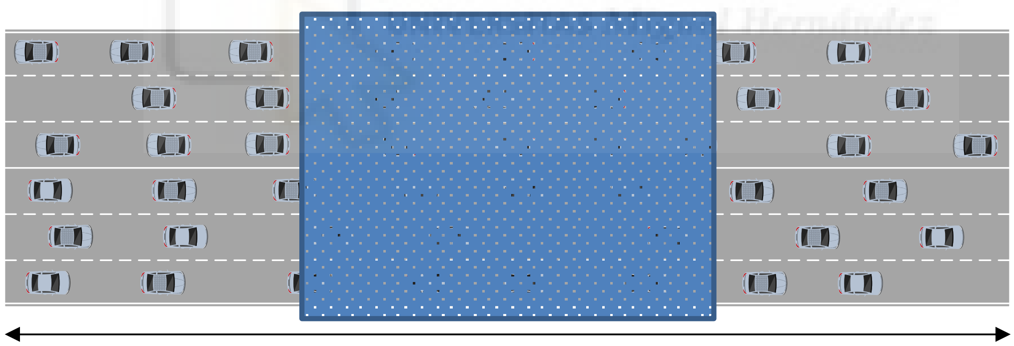


Figure 9. Highway scenario

4.2.2 CPS and CA parameters

In this thesis, the CPM size is dynamically computed based on the number of mandatory and optional containers included in each CPM. The average size for each container in the CPM has been configured following the values presented in Table 3 [58]. Another important aspect in the CPS component is configuring *T_GenCpm*. *T_GenCpm* is a parameter that specifies how often the ETSI CPM generation rules are checked, i.e., the baseline generation rules are checked every *T_GenCpm*. It is specified that *T_GenCpm* must be between 0.1s and 1s (Section 3.4.2). Many existing studies in cooperative perception opted for a default low *T_GenCpm* (e.g., 0.1s)[23][24][25]. Opting for a default low *T_GenCpm* value enables rapid transmission of newly detected objects and provides a higher resolution for the timely transmission of previously detected objects. For example, if an object needs to be included in a CPM every 0.28s based on its speed and *T_GenCpm* value is equal to 0.1s, the object will be included for every 0.3s. However, if *T_GenCpm* is equal to 0.2s, the object will be included for every 0.4s, resulting in a less frequent transmission of the object information. For this reason, *T_GenCpm* is set to 0.1s by default for all the evaluations, and thus the maximum CPM rate is 10 Hz.

Table 3. CPM containers

CPM Container	**Size**
ITS PDU header + Management Container + Station Data Container	121 Bytes
Sensor Information Container	35 Bytes per sensor
Perceived Object Container	35 Bytes per object

The CAM generation rules are implemented in ns3 following ETSI [8]. When CAM generation is enabled in the scenario, vehicles generate CAMs following the CAM generation rules and the size for each CAM is set equal to 350 bytes following [59]. The default *T_GenCam* parameter has been set to 0.1 s, so the maximum CAM rate is 10 Hz. By default, vehicles do not generate CAMs in the simulation scenario and when enabled it is specifically mentioned.

4.2.3 Communication and DCC parameters

By default, all vehicles simulated in the scenarios are equipped with an ITS-G5 transceiver with 100% market penetration rate and use the same channel for message transmissions. The vehicles transmit messages using the 6 Mbps data rate (i.e., QPSK modulation with ½ code rate). The transmission power is set to 23 dBm and the packet sensing threshold to -85 dBm. For radio propagation, Winner+ B1 propagation model is used. The main communications parameters used for the evaluations in this thesis are summarized in Table 4.

Table 4. Communication parameters

Parameter	Values
Transmission power	23 dBm
Antenna gain (tx and rx)	0 dBi
Channel bandwidth	10 MHz
Carrier frequency	5.9 GHz
Noise figure	9 dB
Energy detection threshold	-85 dBm
Data rate	6 Mbps (QPSK 1⁄2)

Regarding the DCC parameters, the DCC Access implements 4 different queues, one for each traffic class. Each queue length is configured to a maximum of 2 messages following [60], and those packets that have been waiting in the queue for a time longer than their lifetime of 1 second will be dropped and not get transmitted. Each queue follows a FIFO scheduling policy so that the packet waiting longer in the queue gets transmitted first. When DCC Facilities is activated, it adapts the equations based on the approach (Reactive or Adaptive) activated in the DCC Access (see Section 3.3.1). Since DCC Facilities controls the number of messages each V2X message service (e.g., CAM and CPM) can generate, it dynamically adapts the *T_GenCpm* and *T_GenCam* values to alter the message generation rate.

4.2.4 Sensor Parameters

Three different sensor configurations are primarily used for the evaluations as shown in Table 4. In the forward sensors' configuration, vehicles are equipped with two forward facing sensors following [5]. The 360º sensor configuration considers a single circular shape sensor with 360º field of view following [5]. The Tesla sensors configuration follows [61] and equips the vehicles with seven sensors. By default, it is considered that the vehicles implement sensor fusion in the evaluated scenarios and the information about an object detected by multiple sensors are reported in the CPM as a single object. When sensor fusion is not used, it is specifically mentioned and the study assumes that the information about an object detected by multiple sensors is reported in the CPM multiple times.

Table 5. Sensor configurations

Sensor	Specification	Range (m)	FOV (º)
Forward	Mid-range radar	65	±40
	Long-range radar	150	±5
360º	Circular radar	150	360
Tesla	Narrow forward camera	250	±15
	Radar	160	±15
	Main forward camera	150	±22
	Forward side cameras	80	±25-115
	Wide forward camera	60	±60
	Rear view camera	50	±115-180
	Rearward side cameras	100	±150-180

4.2.5 Simulation parameters

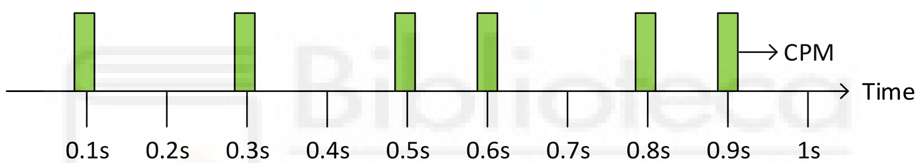
Each evaluated configuration is simulated multiple times in ns3 using different seeds to obtain randomness across multiple simulation runs and ensure sufficient statistical accuracy of the results. The simulator (ns3) initially runs each scenario for around 290 seconds so that vehicles occupy the highway in both driving directions. Starting from 290 seconds, the vehicles enable V2X communications and start transmitting V2X messages like CAMs and CPMs according to the adapted configuration. However, a buffer time is considered for the first 10 seconds (from 290 to 300 seconds) and the generated results are not considered for the evaluation. Starting from 300 seconds to 320 seconds (around 20 seconds), the results are considered for the evaluation and the generated logs are stored in CSV files. The CSV files are then post-processed in Matlab and different metrics are computed (see next section) for the evaluation.

The ns3 simulations and Matlab processing are executed in a high-performance computing cluster made up of 24 high-end multi-processor servers, with more than 250 CPUs, 500GB of RAM and 27TB of storage capacity. The cluster offers a large computational power for the execution of large-scale simulations with a high level of complexity, such as those carried out in the framework of this PhD thesis. It uses specialized process management software to manage the system and supports multithread processing.

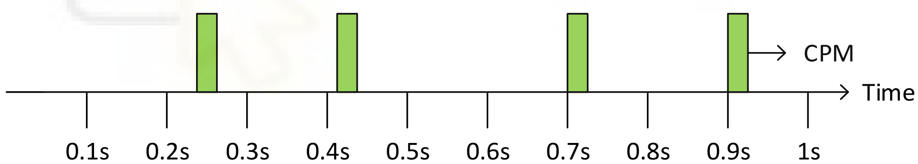
4.3 Evaluation metrics

In this thesis, different metrics are used to evaluate the effectiveness and scalability of cooperative perception. The metrics mainly analyze the operation and perception capabilities of cooperative perception and also the communications performance. This section defines the different metrics used in this thesis.

CPM generation rate: This metric defines the number of cooperative perception messages generated per second per vehicle at the Facilities layer. It is computed in intervals of 1 second for all vehicles in the simulation. From this metric, the average CPM generation rate, or the PDF (Probability Density Function) of the CPM generation rate can be computed. As an example, Figure 10a shows a set of CPMs generated by an ego vehicle at the Facilities layer as a function of time. In this example, the ego vehicle generates 6 CPMs in one second. This metric is used to analyze the operation of cooperative perception.



(a) Ego vehicle generated CPMs at the Facilities layer



(b) Ego vehicle transmitted CPMs at the Access layer

Figure 10. Measurement of CPM generation and transmission rate

CPM transmission rate: This metric defines the number of cooperative perception messages transmitted per second per vehicle at the Access layer. It is also computed in intervals of 1 second for all vehicles in the simulation. From this metric, the average CPM transmission rate and the PDF of the CPM transmission rate can be derived. The main difference between the "*CPM generation rate*" and "*CPM transmission rate*" is that the CPM generation rate computes the CPMs generated at the Facilities layer, and the CPM transmitted rate computes the CPMs actually transmitted at the access layer since not all CPMs generated are transmitted. This difference is particularly important when DCC is activated. The generation rate and transmission rate could vary because DCC could drop or delay CPMs at the Access layer. As an example, Figure 10b shows the CPMs transmitted at the Access layer. In this example, the ego vehicle transmits only 4 CPMs in an interval of 1 second with some delay when compared to the generation time of the CPM at the Facilities layer (see Figure 10a). This metric is used to analyze the operation of cooperative perception, especially when incorporating DCC because DCC could drop packets at the Access layer. If DCC is not considered, all the generated messages at the Facilities layer are transmitted at the Access layer.

Time Between Updates (TBU): This metric defines the time difference between two successive CPMs that receive information about the same object. For every vehicle *i* and object *j*, the time between updates $TBU_{i,j}(d)$ for a distance *d* between object and vehicle receiving the CPM is computed as:

$$TBU_{i,j}(d) = \sum_{k=1}^{M_{i,j}(d)-1} \frac{\Delta T_{i,j}^{k}(d)}{M_{i,j}(d)} \tag{12}$$

where $\Delta T_{i,j}^{k}(d)$ denotes the time difference between two successive CPMs (CPM_k and CPM_{k+1}) received by vehicle *i* that contain information about object *j* when the distance between them is between *d*-Δ*D/2* and *d*+Δ*D/2, with* Δ*D*=25 m. $M_{i,j}(d)$ denotes the number of CPMs received by vehicle *i* that contain information about object *j* when the distance between them is between *d*-Δ*D/2* and *d*+Δ*D/2*. Finally, the computed $TBU_{i,j}(d)$ from every vehicle *i* and object *j* is averaged for every distance *d* and repeated for other distances. This metric can be plotted as the average time between updates as a function of the distance between the detected object and the vehicle receiving the CPMs. This metric is used to analyze how often an object is updated at the receiver with respect to time.

Distance Between Updates (DBU): This metric defines the distance travelled by an object between two successive CPMs received by a given vehicle with information about that object. For every vehicle *i* and object *j*, the distance between updates $DBU_{i,j}(d)$ for a distance *d* is computed as:

$$DBU_{i,j}(d) = \sum_{k=1}^{M_{i,j}(d)-1} \frac{\Delta \overline{D}_{i,j}^{k}(d)}{M_{i,j}(d)} \tag{13}$$

where $\Delta \overline{D}_{i,j}^{k}(d)$ denotes the travelled distance between two successive CPMs (CPM_k and CPM_{k+1}) received by vehicle *i* that contain information about object *j* when the distance between the vehicle and the object is between *d*-Δ*D/2* and *d*+Δ*D/2*. $M_{i,j}(d)$ denotes the number of CPMs received by vehicle *i* that contain information about object *j* when the distance between them is between *d*-Δ*D/2* and *d*+Δ*D/2*. Finally, the computed $DBU_{i,j}(d)$ from every vehicle *i* and object *j* is averaged for every distance *d* and repeated for other distances. This metric can be plotted as the average distance between updates as a function of the distance between the detected object and the vehicle receiving the CPMs. This metric is used to analyze the distance traveled by the object between the two successive received updates.

Information Age (IA): The information age metric is defined as the difference between the time the CPM is generated at the Facilities layer of the transmitter and the time the CPM has been received at the receiver. In this metric, the distance between the transmitter and receiver does not have a significant impact because the propagation delay is negligible. For every vehicle *i*, the information age IA_i is computed as:

$$IA_i = \sum_{k=1}^{M_i} \frac{\Delta T_k}{M_i} \tag{14}$$

where ΔT_k is the difference between the time the CPM_k is generated at the transmitter and the time the CPM_k has been received at the receiver. M_i denotes the number of CPMs received by vehicle *i*. This metric is used to analyze the time taken for a packet to reach the destination since the packet is generated. This information is particularly useful when DCC is activated because DCC could additionally delay the transmission of the packets due to queuing.

Channel Busy Ratio (CBR): The CBR metric is defined as the percentage of time that the channel is sensed as busy and is calculated following the ETSI Technical Specification in [62] as:

$$CBR = \frac{T_{busy}}{T_{CBR}} \tag{15}$$

In this equation, T_{busy} is the time during which the strength of received signals exceeds -85 dBm. T_{busy} is computed over a period of T_{CBR} = 100 ms following [62]. The process used to compute the CBR is illustrated in the example of Figure 11, which plots the received signal as a function of time, during a T_{CBR} period. In this example, 3 packets arrive to the radio interface, but only packets 1 and 3 are received with a signal strength higher than -85 dBm. Therefore, T_{busy} is equal to the time duration of these two packets, highlighted in green in the figure. When there is a packet collision, the same procedure is followed, but the overlapping part is only added once to T_{busy}. This is one of the main metrics for analyzing the communications performance and it is mainly used to estimate the channel load generated in the network.

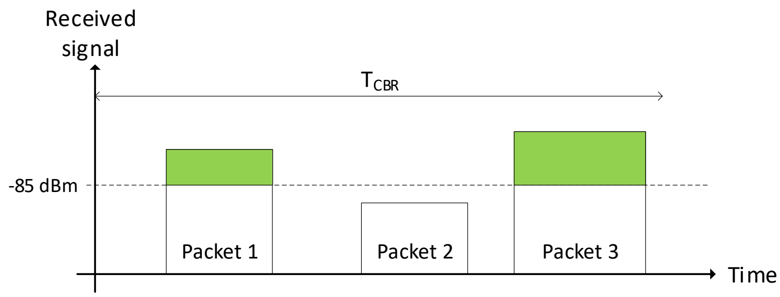


Figure 11. Measurement of CBR.

Packet Delivery Ratio (PDR): the *PDR(d)* metric is defined as the probability of correctly receiving a packet at a given distance *d* to the transmitter. The PDR is calculated for a given transmitting vehicle *j* as:

$$PDR_j(d) = \frac{\sum_{i=1}^{N} X_{i,j}(d)}{\sum_{i=1}^{N} Y_{i,j}(d)} \qquad (16)$$

In this equation, $Y_{i,j}(d)$ is the number of vehicles that are located at a distance between d-$\Delta D/2$ and $d+\Delta D/2$ to the transmitter when the transmitter transmits packet *i*. $X_{i,j}(d)$ is the number of vehicles that successfully receive such packet *i*. Note that $X_{i,j}(d) \leq Y_{i,j}(d)$ and therefore $PDR_j(d) \leq 1$. *N* denotes the number of transmitted messages and ΔD=25 m. The overall PDR at a given distance is computed as the average of all transmitting vehicles *j*. This is also one of the main metrics for analyzing the communications performance and it is mainly used to analyze the ratio of successfully received packets.

Object Perception Ratio (OPR): The OPR metric is used to measure the perception capabilities. This metric is defined as the probability to detect an object within a given time window ΔT thanks to the exchange of CPMs. It is considered that a vehicle successfully detects an object if it receives at least one CPM with information about that object during ΔT. The time window has been set equal to the time required by the CPM generation rules for a vehicle to send an update about a detected object considering the speed of the object. This adaptation has been done to fairly measure the OPR for objects moving at different speeds. For example, an object that is stopped will only be included in a CPM once every second by a vehicle detecting it. However, an object moving at 100 km/h will be included every 200 ms. The time window ΔT is therefore dynamically computed for each object based on its speed S as $\Delta T = T\_GenCpm \cdot \lceil 4 \cdot S^{-1} \cdot T\_GenCpm^{-1} \rceil$, with $\Delta T \leq 1$ s. This computation considers that an object moving at speed S is included in a CPM every time it has moved 4m, and that the CPM period is a multiple of *T_GenCpm*. Considering *T_GenCpm*=100 ms (0.1 s), Figure 12 plots the resulting time window as a function of the object speed.

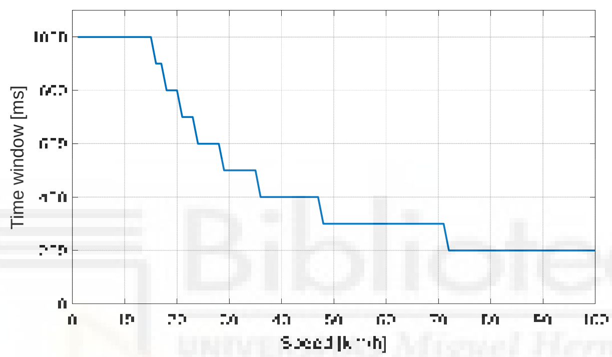
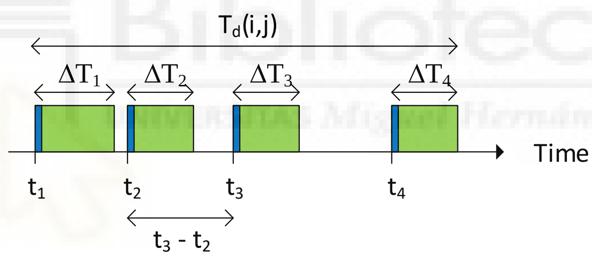


Figure 12. Time window as a function of the speed.

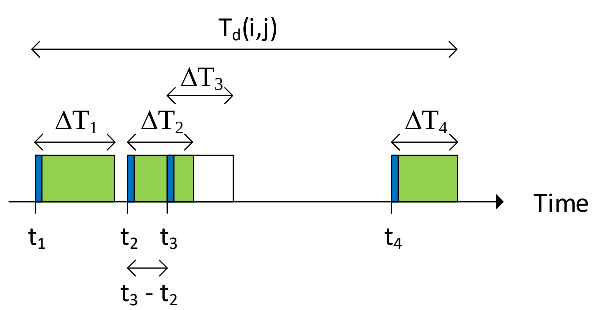
Every time a new CPM is received with information about an object, its ΔT is updated. Considering this dynamic adaptation of the time window, the OPR metric of vehicle *i* and object *j* is:

$$OPR_{i,j}(d) = \frac{S_{i,j}(d)}{T_{i,j}(d)} \quad (17)$$

$T_{i,j}(d)$ is the time during which object *j* is located at a distance between d-$\Delta D/2$ and d+$\Delta D/2$ from vehicle *i*. $S_{i,j}(d)$ is the time during which vehicle *i* has successfully detected object *j* and their distance was between d-$\Delta D/2$ and d+$\Delta D/2$; note that $S_{i,j}(d) \leq T_{i,j}(d)$. To calculate $S_{i,j}(d)$, it is taken into account all the CPMs received by vehicle *i* during the time interval $T_{i,j}(d)$ that contained information about object *j*. Figure 13 illustrates how the received CPMs are taken into account. Figure 13a considers, as an example, that 4 CPMs were received during $T_{i,j}(d)$ at t_1, t_2, t_3 and t_4. Every time a new CPM is received, the object is considered successfully detected during time window ΔT. Therefore, the green areas in Figure 13a illustrate the time during which the vehicle has successfully detected the object. The ratio between $S_{i,j}(d)$ and $T_{i,j}(d)$ is $\mathrm{OPR}_{\mathrm{i,j}}(d)$. If the green areas do not overlap, as in Figure 13a, the calculation of $S_{i,j}(d)$ is relatively simple since it is equal to the sum of the time duration of all the green areas. However, when two CPMs are consecutively received (e.g., coming from different transmitting vehicles), it needs to consider the time interval between them. This is illustrated in Figure 13b for CPMs 3 and 2. As it can be observed, the time window of the second CPM (ΔT_2) is higher than the time interval between the reception of the second and third CPMs (t_3-t_2). As a result, the green areas associated to these two CPMs overlap. To avoid taking into account this overlapping area twice in the computation of $S_{i,j}(d)$, the minimum between t_{k+1} - t_k and ΔT_k for a given CPM received at t_k has to be considered. More specifically, $S_{i,j}(d) = \sum_k s_{i,j}^k(d)$, where $s_{i,j}^k(d)$ is the minimum between t_{k+1} - t_k and ΔT_k. Finally, the OPR metric at a distance d is computed as the average value of $OPR_{\boldsymbol{i,j}}(d)$ for all vehicles i and all objects j. ΔD has been set equal to 25 m in this study. This is one of the main metrics for analyzing the performance of cooperative perception techniques.



(a) All intervals between received CPMs are higher than their corresponding time windows



(b) CPMs 2 and 3 are received with an interval lower than the time window ΔT_2

Figure 13. Computation of the OPR metric.

Detected Object Redundancy (DOR): The DOR metric is defined as the number of updates received within a given time window ΔT about the same object through the reception of CPMs. For every vehicle *i* and object *j*, the detected object redundancy $DOR_{i,j}(d)$ for a distance *d* is computed as:

$$DOR_{i,j}(d) = \sum_{k=1}^{M_{i,j}(d)} R_{i,j}(d) \quad (18)$$

where $R_{i,j}(d)$ denotes the successful reception of object *j* received by vehicle *i* when the distance between them is between d-$\Delta D/2$ and d+$\Delta D/2$. $M_{i,j}(d)$ denotes the number of CPMs received by vehicle *i* that contain information about object *j* when the distance between them is between d-$\Delta D/2$ and d+$\Delta D/2$. Finally, the computed $DOR_{i,j}(d)$ from every vehicle *i* and object *j* is averaged for every distance *d* and repeated for other distances. This is also one of the main metrics used for analyzing the performance of cooperative perception techniques, and it is mainly used to analyze the redundancy and efficiency of the proposed techniques.

5 Dimensioning Cooperative Perception

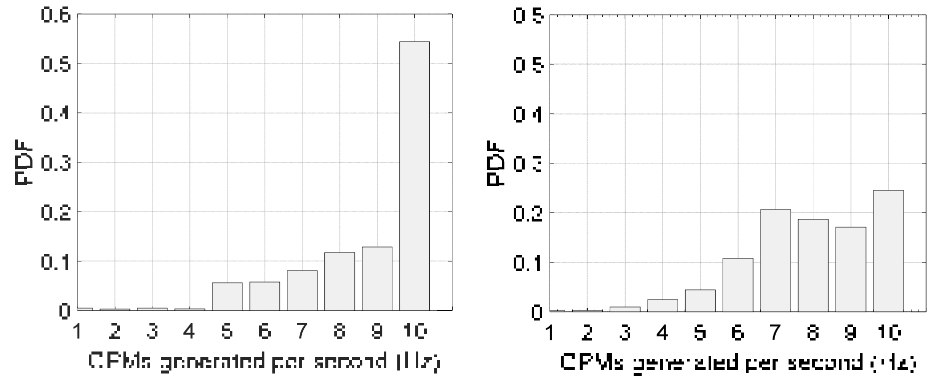
In this chapter, a detailed dimensioning study has been carried out to investigate the the operation and performance of cooperative perception and the impact of different factors. To this aim, Section 5.1 performs a benchmark evaluation on the message generation rules defined by ETSI (referred to as baseline generation rules) and compares it with periodic message generation policies to analyze its effectiveness and identify any potential inefficiencies. Section 5.2 then analyzes the impact of the traffic density, the sensors' characteristics and the market penetration rate on the effectiveness of cooperative perception considering the ETSI message generation rules. Section 5.3 studies the impact of congestion control on cooperative perception using the DCC framework defined by ETSI. In particular, the combination of DCC functions at Access and Facilities layers are analyzed in detail. Finally, Section 5.4 concludes this chapter by providing a summary of the analysis performed, as well as a list of the details and additional results that can be found in the corresponding publications, included in Annex A.1 and Annex A.2. Also, the analysis performed in Section 5.1 and Section 5.3 have been presented to ETSI Collective Perception Service standard meetings. The analysis performed on the different message generation rules (Section 5.1) has been incorporated as part of the ETSI CPS technical report [5] which provides a more in-depth analysis including the analysis of different sensor configurations and additional metrics.

5.1 Analysis of message generation rules

This section conducts a benchmark evaluation of message generation rules that define when vehicles should generate collective perception messages and what should be their content. The generation rules are important because they can have a significant impact on the effectiveness of cooperative perception and on the vehicular network. In fact, if vehicles exchange information about detected objects very frequently, they could improve their perception capabilities and be able to detect their surrounding objects with higher accuracy. However, a too frequent exchange of CPM messages can also saturate the communications channel to the point that these messages cannot be transmitted or are significantly delayed, ultimately reducing the effectiveness of cooperative perception. This section analyses the baseline generation rules defined in Section 3.4.2 and in ETSI's technical report in [5] along with two different periodic message generation policies that generate CPMs at a constant rate of 10 Hz (*T_GenCpm*=0.1s) or 2 Hz (*T_GenCpm*=0.5s). This analysis is carried out on the highway scenario described in Section 4.2.1 under low and medium traffic densities. By default, all vehicles are equipped with an ITS-G5 transceiver with 100% market penetration rate of cooperative perception and the evaluation is performed considering only the forward sensors configuration (see Section 4.2.4). The DCC is not activated in this scenario to concentrate only on the impact of the message generation rules.

5.1.1 Operation

We first analyze the operation of the baseline generation rules since the periodic policies generate CPM at the constant rate. Figure 14 represents the Probability Density Function (PDF) of the number of CPMs generated per second per vehicle for the baseline generation rules under the two traffic densities. The number of CPMs generated per vehicle with the baseline generation rules depends on the number of detected vehicles (i.e., traffic density) and on their dynamics (e.g., an object is included in a CPM every 4m). As a result, vehicles generate more CPMs per second at low densities (Figure 14 a) than at medium densities (Figure 14b) because the speed of vehicles is higher for low traffic densities. However, not all vehicles generate CPMs at the same rate in a given traffic density scenario since the speed limit varies per lane (Table 2). It is also interesting to analyze with more detail the medium traffic density scenario (Figure 14b). In medium density, vehicles move between 70 km/h and 59 km/h and change their absolute position by more than 4 m every 300 ms. Vehicles that detect this change then generate CPM at 3.3 Hz on average. However, Figure 14b shows that there are vehicles that transmit 6-10 CPMs per second. This is due to the fact that vehicles detect objects (i.e., vehicles) at different time intervals (objects constantly enter and leave the sensor detection range of a transmitting vehicle at different times) and the detected objects need to be included in different CPMs. This increases the frequency of the generation of CPMs as high as 10 Hz in the medium traffic density scenario (Figure 14b) [58].



(a) Low traffic density (b) Medium traffic density

Figure 14. PDF (Probability Density Function) of the number of CPMs generated per second and per vehicle with the baseline generation rules.

Figure 15 represents the PDF of the number of objects included in each CPM for the periodic and baseline generation rules under the two traffic densities. The figure shows that the periodic policies augment the size of CPMs because it always includes all the detected objects in the CPM. The baseline generation rules control the CPM size by including the detected objects based on their dynamics. As the traffic density increases, the number of objects included in each CPM increases with the periodic policies because more objects (i.e., vehicles) are detected. However, Figure 15 shows that the traffic density does not significantly affect the number of objects included in each CPM with the baseline generation rules. This is the case because the speed of vehicles decreases with the traffic density and as a result objects need to be reported in a CPM less frequently. This clearly shows that the baseline generation rules adapt the number of objects included in each CPM to the traffic density and speed. However, the figure shows that the baseline generation rules generate CPMs that report information about a small number of detected objects. Under certain situations, this could unnecessarily increase the number of channel access attempts and redundant headers which could result in a loss of efficiency. Such efficiency should be addressed to improve the scalability of cooperative perception and vehicular networks [58].

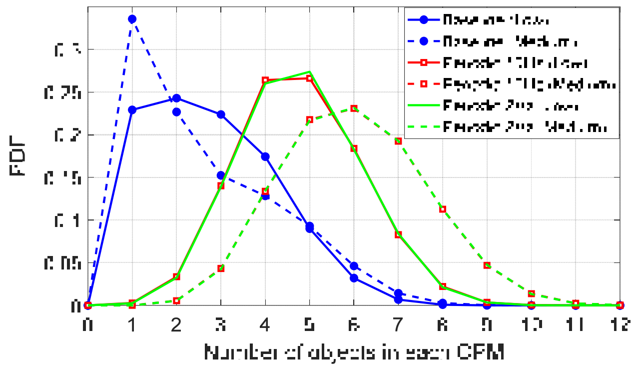


Figure 15. PDF (Probability Density Function) of the number of objects included in each CPM with the baseline and periodic policies.

5.1.2 Communications performance

This section evaluates the impact of the generation rules on the communications performance. To this aim, Table 6 shows the average CBR experienced when implementing each CPM generation policy under the two traffic densities. Table 6 shows that the periodic policy operating at 2 Hz is the one generating the lowest channel load. On the other hand, the periodic policy at 10 Hz generates the highest channel load. The baseline generation rules generate intermediate channel load levels (Table 6) in line with the results depicted in Figure 14 and Figure 15. These results showed that the baseline generation rules generate between 4 and 10 CPMs per second, approximately, and reduce the number of objects per CPM compared to the periodic policies. Table 6 shows that the channel load increases with the traffic density. However, lower increases are observed with the baseline generation rules. In particular, an increase in the traffic density augments the CBR experienced by the baseline generation rules by a factor of 1.6, whereas it increases by factors of 2.1 (2 Hz) and 1.9 (10 Hz) for the periodic policies [58].

Table 6. Average CBR

Policy	**Traffic density**	**CBR**
Periodic at 2Hz	Low	5.6 %
	Medium	11.9 %
Periodic at 10Hz	Low	25.6 %
	Medium	49.6 %
Baseline	Low	19.2 %
	Medium	31.7 %

5.1.3 Perception capabilities

This section analyzes the perception capabilities of vehicles achieved with different CPM generation policies. It is assumed that a vehicle successfully detects an object if it receives at least one CPM with information about that object during the period of one second. To this aim, Figure 16 depicts the object perception ratio that shows that all policies achieve a high perception (higher than 0.989) up to 350 m. Beyond 350 m, the perception degrades significantly under higher densities for the baseline generation rules and the periodic policy at 10 Hz as a result of the higher CBR (Table 6). On the other hand, the perception degrades under both densities for the periodic policy at 2 Hz because this policy transmits less CPMs and the propagation loses affect more negatively the perception.

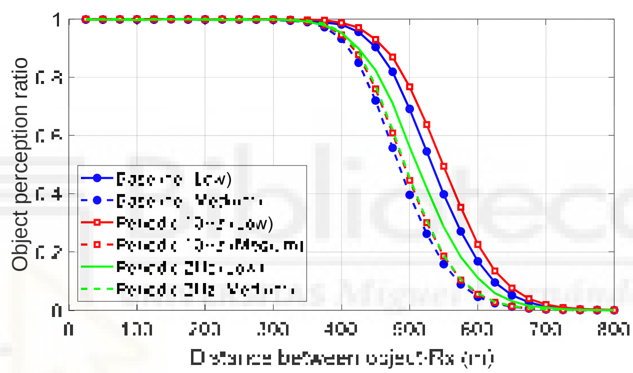


Figure 16. Object perception ratio as a function of the distance between the detected object and the vehicle receiving the CPM.

Figure 17 illustrates the detected object redundancy experienced with different CPM generation policies. Figure shows that the periodic policy at 10 Hz provides around 51 updates per second of the same object at short distances. The baseline generation rules can reduce this value to around 30 updates per second without degrading the perception (Figure 16). In addition, the baseline generation rules can improve the communications performance by reducing the channel load (Table 6). Despite the gains observed with the baseline generation rules, it is yet to be decided whether the high redundancy levels observed in Figure 17 are necessary for a safe connected and automated driving or not.

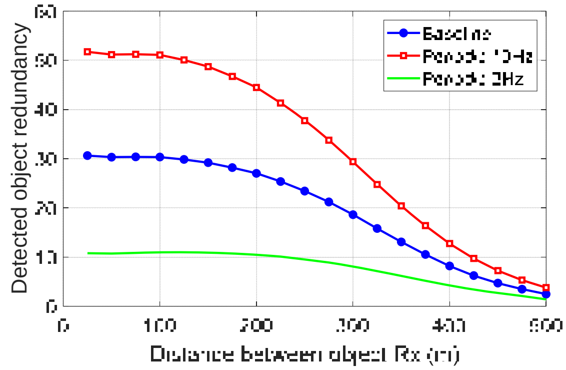


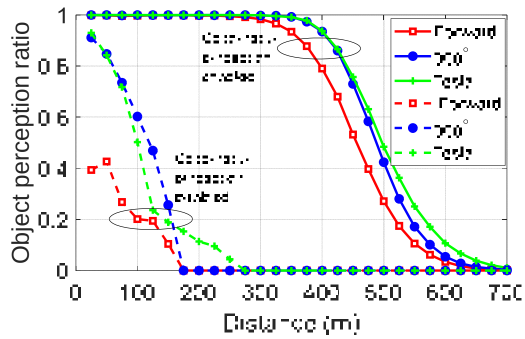
Figure 17. Detected object redundancy as a function of the distance between the detected object and the vehicle receiving the CPM under medium density.

5.2 Evaluation of cooperative perception

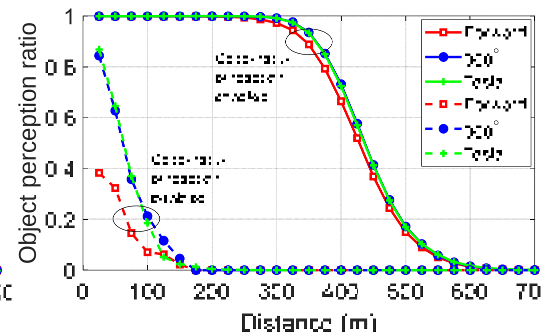
This section aims to analyze the impact of the sensors' characteristics and the market penetration rate on the operation and performance of cooperative perception. To this aim, the highway scenario (see Section 4.2.1) with low, medium and high traffic densities are considered and all the sensor configurations such as the forward, 360º and Tesla sensors configurations (see Section 4.2.4) are studied. By default, all vehicles are equipped with an ITS-G5 transceiver except in the analysis performed on the impact of the Market Penetration Rate (MPR). All vehicles by default generate CPMs following the baseline generation rules.

5.2.1 Sensors' characteristics

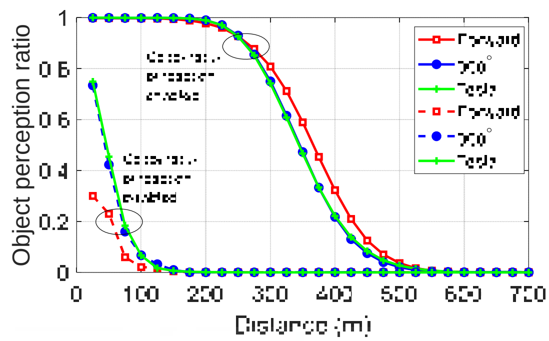
The perception capabilities of different sensor configurations with and without using cooperative perception are initially evaluated. To this aim, Figure 18 compares the average object perception ratio with and without using cooperative perception for the three different sensor configurations under all traffic densities. Figure 18 shows that the perception achieved without cooperative perception is limited due to the occlusion of objects and the degradation increases with the distance and the traffic density. This is the case because both factors augment the probability of vehicles blocking the sensors' line of sight. Figure 18 also shows that the perception capabilities augment with the sensors' FoV and range. In this case, using the forward sensors alone reduces the object perception ratio since these sensors cannot detect vehicles in all directions [2].



(a) Low density



(b) Medium density



(c) High density

Figure 18. Object perception ratio under different traffic densities. When using cooperative perception, the x-axis represents the distance between the detected object and the vehicle receiving the CPM. When cooperative perception is not used, the x-axis represents the distance between the detected object and the vehicle detecting it with its sensors.

By enabling cooperative perception, the perception capabilities of CAVs significantly increase as shown in Figure 18. In particular, it increases the distance at which objects can be detected for all sensor configurations and mitigates sensors limitations. In this case, the Tesla and 360º sensor configurations achieve similar perception rates, and the perception with the forward sensor configuration slightly degrades at medium to large distances for low traffic densities (Figure 18a). This is the case because cooperative perception compensates the perception limitations of sensors. For example, a vehicle that uses only forward sensors can detect objects from behind when using cooperative perception, thanks to the CPMs received from other vehicles that detect these objects. We should note that the slight perception degradation observed in Figure 18 with the forward sensor configuration is reduced for higher traffic densities. This is the case because at higher densities more vehicles detect each object and cooperative perception can better compensate the limitations of the forward sensors [2].

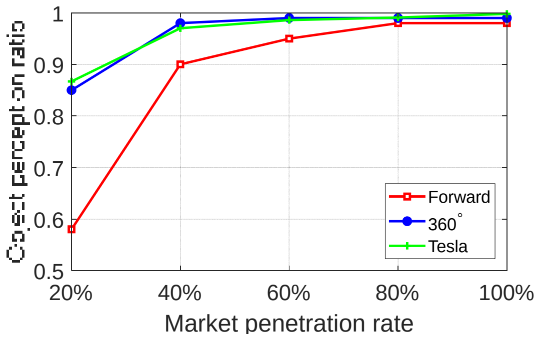
Figure 18 also reveals that the object perception ratio significantly decreases when the traffic density increases. This degradation is due to the increase in the channel load at higher traffic densities as shown in Table 7. Table 7 shows that the 360º and Tesla sensor configurations can increase the CBR by around 40% compared with the forward sensor configuration. Thanks to the lower channel load generated, the forward sensor configuration is able to provide a higher cooperative perception ratio than the 360º and Tesla sensor configurations for the high traffic density scenario (Figure 18c).

TABLE 7. Average CBR (Channel Busy Ratio)

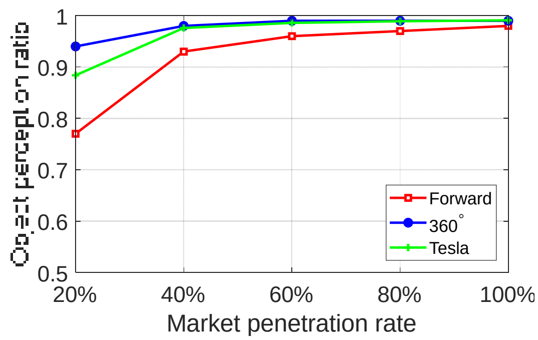
Traffic density	**Sensor configuration**		
	Forward	**360º**	**Tesla**
Low	19.2%	27.6%	27.6%
Medium	31.8%	44.4%	44.4%
High	52.4%	71.3%	71.6%

5.2.2 Market Penetration Rate

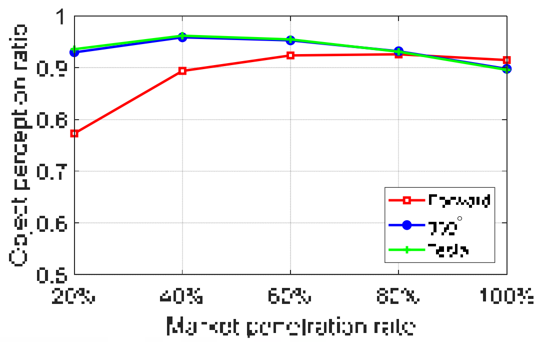
The effectiveness of cooperative perception also depends on the number of vehicles that detect objects and share their information. Figure 19 shows the impact of the MPR on cooperative perception. The figure shows that the object perception ratio increases as the MPR increases, with the low and medium traffic densities. However, when the traffic density is high, the perception ratio decreases for MPRs above 40% (Figure 19c). This degradation is again due to the significant increase of channel load at high traffic densities and the consequent increase in packet losses due to collisions. Figure 19 also shows that the sensor configuration does have an important effect on the perception when the MPR is low. In particular, the 360º and Tesla sensor configurations achieve significantly higher perception ratios than the forward sensor configuration, especially for low MPR. This is the case because cooperative perception cannot compensate well with the perception limitations of the forward sensor configuration when there are few vehicles and not all vehicles can detect objects and share their information. However, all the sensor configurations achieve perception levels higher than 90% from 40% of MPR and the achieved perception levels are similar from MPR above 80% [2].



(a) Low density



(b) Medium density

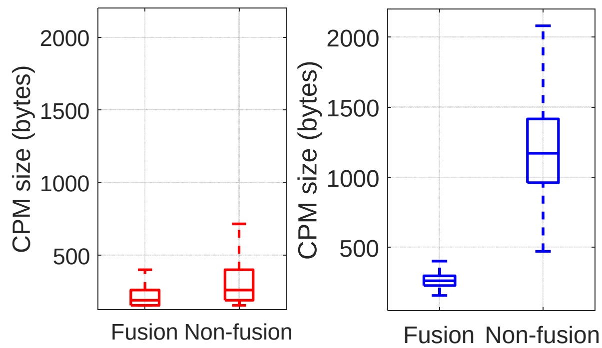


(c) High density

Figure 19. Object perception ratio under different traffic densities for different market penetration rates and for distances up to 350m.

5.2.3 Sensor fusion and non-fusion

By default, vehicles implement sensor fusion and an object detected by multiple sensors are reported once in the CPM (i.e., one perceived object container per detected object). If sensor fusion is not used, an object detected by multiple sensors is reported multiple times in each CPM. This increases the message size as shown in Figure 20. This figure compares the CPM size with and without sensor fusion for the medium traffic density scenario under the forward and Tesla sensor configurations. The results are presented as a box plot with the bottom and top edges of the box indicating the 25th and 75th percentiles and the mark in the middle representing the median. The vertical lines in the box plot represent the most extreme data points. The results obtained show that the CPM size significantly increases when sensor fusion is not used, especially for the Tesla sensor configuration since it has more on-board sensors. The main concern related to the increasing message size is that it significantly augments the channel load and the interference. This could degrade the effectiveness of cooperative perception as shown in Figure 21. The figure clearly shows how the object perception ratio degrades when sensor fusion is not applied and the degradation is particularly relevant when the traffic density increases [2].



(a) Forward (b) Tesla

Figure 20. CPM size for medium traffic density under the forward and Tesla sensor configurations. Similar trends have been observed with low and high traffic densities for both sensor configurations.

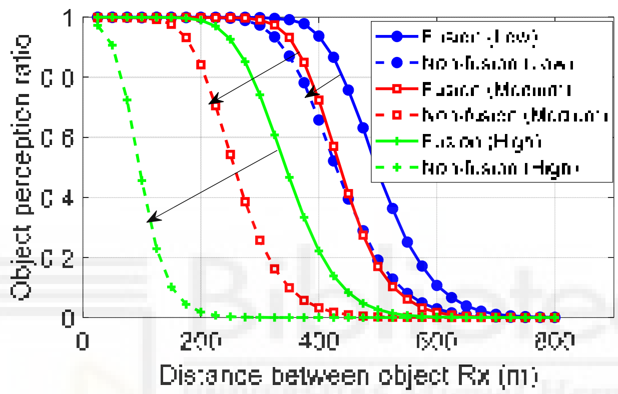


Figure 21. Object perception ratio as a function of the distance between the detected object and the vehicle receiving the CPM under different traffic densities (low, medium and high). These results correspond to the Tesla sensor configuration. The arrows highlight the degradation produced when sensor fusion is not used.

5.3 Impact of congestion control on cooperative perception

Cooperative perception relies on the correct reception of the exchanged V2X messages. However, the previous analysis performed in this chapter shows that the cooperative perception can increase the channel load quite significantly under certain scenarios and configurations which could impact the performance of V2X communications and the system's scalability. To prevent this, an increase of the channel load above a certain threshold activates the DCC mechanisms for congestion control. DCC effectively controls the channel load, however, it can alter the performance and operation of cooperative perception. This can occur, for example, if the DCC queues CPM messages. Queuing would increase the information age and alter the regular reception of object updates. The DCC could also drop CPMs when the CPM generation rate is higher than the maximum transmission rate allowed by DCC Access, because the queues would be overloaded. This could also significantly impact the effectiveness of cooperative perception. In addition, it is also important to highlight that the CPM might have to coexist with other messages in the same channel. This increases the risk that DCC impacts the operation and effectiveness of cooperative perception. In this context, this section analyses the impact of DCC on cooperative perception. In particular, the combination of DCC at the Access layer and DCC at the Facilities layer are considered for the analysis because these two DCC components mostly affect the transmission of CPM messages.

To this aim, the evaluation considers the highway scenario (see Section 4.2.1) with high traffic density and vehicles are equipped with the 360º sensor configuration (see Section 4.2.4). By default, 100% MPR is considered and vehicles transmit CAMs and CPMs in the same channel. The CPMs are generated following the baseline generation rules defined in Section 3.4.2 and the CAMs are generated following [8]. The DCC profile for CPM is set to DP2 or DP3 depending on the simulation (its value has not been decided yet in ETSI), and the DCC profile of the CAM is set to DP2 following [63].

5.3.1 DCC Access

The channel load increases with the transmission of both CAMs and CPMs when DCC is not activated. For example, the CBR is equal to 75% in the high density scenario when DCC is not activated. The use of DCC Access can significantly reduce the CBR as shown in Table 8. In particular, the Reactive approach reduces more aggressively the channel load and maintains the CBR at around 37%. The Adaptive approach is designed to converge to the target CBR of 68% and this results in higher CBR levels. Table 8 also shows that nearly the same CBR is achieved independently of the DCC profiles of the messages because of the similar packet transmission rates [2].

Table 8. Average CBR

DCC profile	**DCC Access**	
	Reactive	**Adaptive**
Different (CAM=DP2 and CPM=DP3)	36.9%	62.1%
Same (CAM=CPM=DP2)	37.8%	61.9%

DCC Access can reduce the CBR and improve the PDR at the radio level, i.e., the ratio between the received and transmitted packets. This is particularly the case with the

Adaptive approach as shown in Figure 22. The figure also shows that the Reactive approach actually degrades the PDR at the radio level despite reducing the CBR. This is the case because with the Reactive approach vehicles tend to synchronize with each other and change their state (and thus their T_{off}) nearly at the same time [34]. As a result, vehicles generate a significant amount of packet collisions. Packet collisions reduce the channel load (and CBR) because when packets collide they overlap in time. Similar results are obtained when analyzing the PDR at the radio level when CAMs and CPMs have different DCC profiles [2].

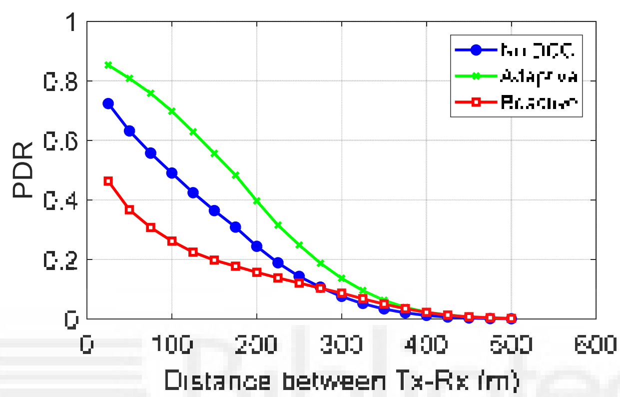
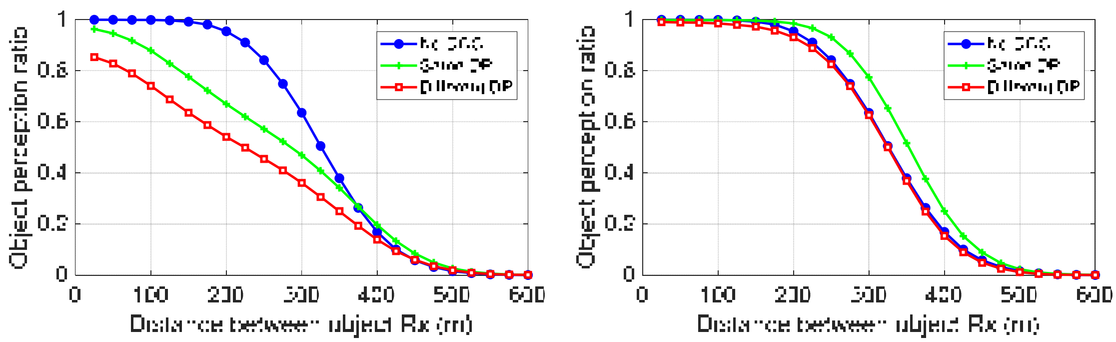


Figure 22. PDR (Packet Delivery Ratio) at the radio level as a function of the distance between transmitter and receiver without and with DCC Access when CAMs and CPMs have the same DCC profile.

The communications trends observed impact on the performance of cooperative perception. Figure 23a shows that the perception significantly degrades with the Reactive approach following the trend observed in Figure 22. This once again clearly proves that the Reactive approach degrades the performance of cooperative perception despite reducing the channel load. On the other hand, Figure 23b shows that the Adaptive approach improves the object perception ratio for distances beyond 200 m when CAMs and CPMs have the same DCC profile. This effect is produced due to the different nature of packet errors with and without DCC. When DCC is not applied, more packet collisions are produced due to the higher channel load. Therefore, when two (or more) packets collide, more than one packet can be lost due to such collision. This effect is not produced with the packets dropped by DCC, since one packet drop does not affect the reception of other packets. With different DCC profiles, the Adaptive approach achieves a perception similar to the configuration where DCC is not activated. In both cases, the Adaptive approach reduces the CBR by 17% when compared to the scenario where DCC is not activated.



(a) Reactive (b) Adaptive

Figure 23. Object perception ratio as a function of the distance between the detected object and the vehicle receiving the CPM without DCC and with DCC Access.

The previous results show that DCC Access has an impact on the perception. However, they do not quantify the freshness of the received information. To this aim, Figure 24 represents the information age obtained without DCC and with DCC Access (Reactive and Adaptive) when CAMs and CPMs are configured with the same and different DCC profiles. The bars represent the mean values and the vertical lines correspond to the 5th and 95th percentiles. The results show that the DCC Access significantly increases the information age when compared to the scenario without DCC. When DCC is not used, all the generated CPMs are immediately transmitted. However, with DCC, the generated CPMs must often wait in the queue before transmission. This waiting time causes the received information to be outdated by up to 0.4s (Adaptive approach) or 0.5s (Reactive approach) when CAM and CPM have different DCC profiles. This is a non-negligible time that can degrade the effectiveness of cooperative perception when implementing DCC. This is despite the possibility to achieve a higher object perception ratio (Figure 23) since detecting more objects is not useful if the information about the detected objects is outdated or not sufficiently fresh [2].

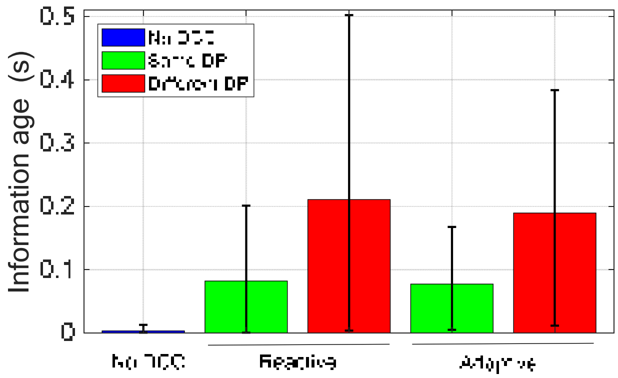


Figure 24. Average information age for CPMs received with and without DCC Access. The bars represent the average values and the vertical lines represent the 5th and 95th percentiles.

5.3.2 DCC Facilities

DCC Facilities can help mitigate the increase of the information age caused by DCC Access by adapting the message generation to the rate tolerated by DCC Access. To this aim, DCC Access reports to DCC Facilities the amount of resources available, and DCC Facilities distributes them among the different services taking into account their DCC profile. To effectively share the resources between CAMs and CPMs, this analysis is performed considering only the same DCC profile, DP2, for both CAMs and CPMs.

Figure 25 compares the information age obtained without DCC, with DCC Access only and with the combination of DCC Access and DCC Facilities. As it can be observed, DCC Access significantly increases the information age as previously shown. However, the combination of DCC Facilities and DCC Access significantly reduces the information age when the Adaptive approach is considered. This improvement is achieved because DCC Facilities controls the message generation following the limits provided by DCC Access so that messages are not generated if they are going to be queued. The information age is not improved with the combination of DCC Facilities and DCC Access with the Reactive approach because the channel load variations do not allow DCC Facilities to accurately track the packet transmission rate (Table 1) and hence increase the queuing time.

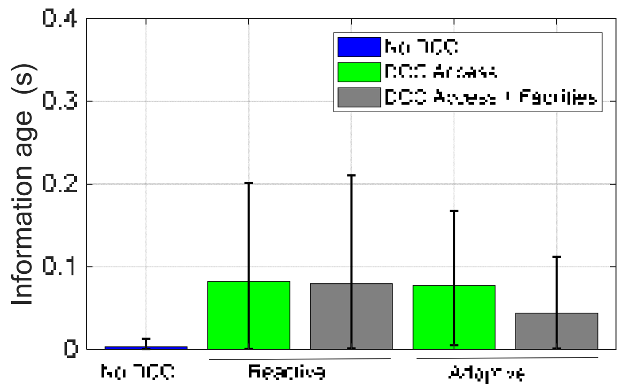


Figure 25. Average information age for CPMs received when CAMs and CPMs have the same DCC profile. The bars represent the average values and the vertical lines represent the 5th and 95th percentiles.

The control of DCC Facilities on the CPM generation rate can be observed from Figure 26 that shows the PDF of the number of CPMs generated at the Facilities layer per second per vehicle. Figure shows that the configurations with DCC Access only and without DCC generate the same number of CPMs. This is the case because DCC Access controls the transmission rate of the CPMs, but it does not modify the CPM generation. The figure also shows that DCC Facilities reduces the number of CPMs generated per second to satisfy the DCC Access limit. As a consequence, it increases the number of objects included in each CPM as shown in Figure 27. This is the case because the time interval between CPM generations is longer, and thus more objects satisfy the conditions to be included in a CPM since the last time a CPM was generated. Despite the variation observed in the number of CPMs generated per second and the number of objects contained in each CPM, the combination of DCC Facilities and DCC Access with the Adaptive approach maintains the CBR around 61.9%, which is similar to the one achieved with only DCC Access (Table 8). This demonstrates that the DCC Facilities maintains the CBR tolerated by DCC Access, but not more. However, the combination of DCC Facilities and DCC Access with the Reactive approach has a different effect on the CBR. It increases the CBR to 46.7% compared to the scenario when only DCC Access is used (37.8%). This increase is produced because DCC Facilities mitigates the synchronization problem in this case by allowing each vehicle to generate (and transmit) messages with different time intervals based on their past generated messages. Mitigating the synchronization problem increases the CBR because there are less packet collisions and thus packets do not overlap in time [2].

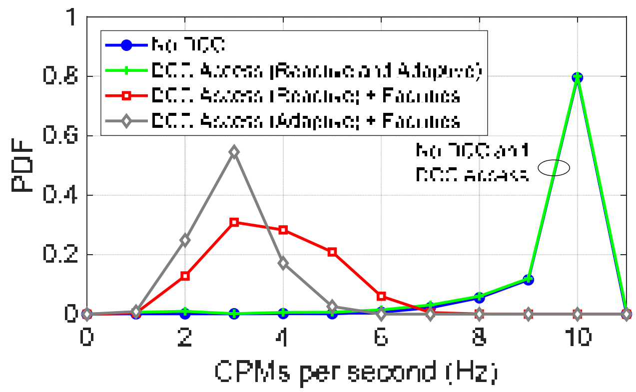


Figure 26. PDF of the number of CPMs generated at the Facilities layer per second per vehicle when CAMs and CPMs have the same DCC profile. When DCC Access is used alone, the same results are obtained for Reactive and Adaptive approaches since DCC Access does not modify the generation of CPMs.

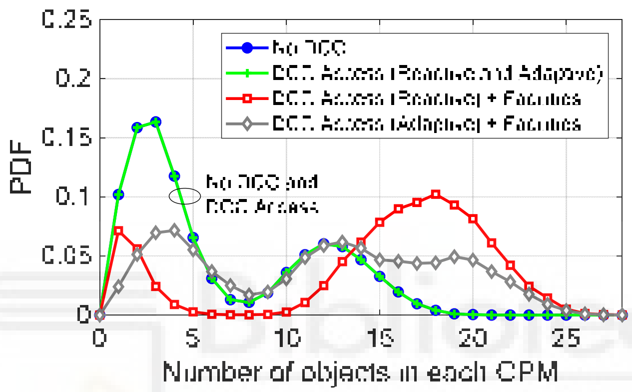
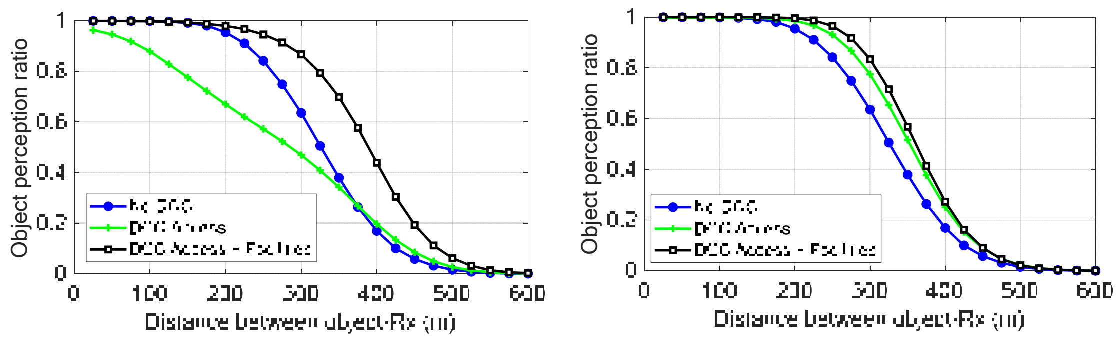


Figure 27. PDF of the number of objects included in each CPM when CAMs and CPMs have the same DCC profile. When DCC Access is used alone, the same results are obtained for Reactive and Adaptive approaches.

The communications effects observed have an impact on the perception achieved when DCC Facilities is enabled. Figure 28 compares the object perception ratio when not using DCC, when using DCC Access only and when combining DCC Access and DCC Facilities. Figure 28a shows that the combination of DCC Facilities and DCC Access with the Reactive approach mitigates the synchronization problem and improves the perception. In fact, the combination of DCC Facilities and DCC Access with the Reactive approach slightly outperforms the combination of DCC Facilities and DCC Access with the Adaptive approach for distances beyond 300 m. This improvement is produced due to the lower CBR achieved with Reactive (46.7%) when compared to the CBR achieved with Adaptive (61.9%) that reduces the packet collisions. All these results clearly show that the combination of DCC Facilities and DCC Access can significantly improve cooperative perception. This is the case because the combination augments the object perception ratio, reduces the information age, and improves the PDR compared to the scenario with DCC Access only.



(a) Reactive (b) Adaptive

Figure 28. Object perception ratio as a function of the distance between the detected object and the vehicle receiving the CPMs when CAMs and CPMs have the same DCC profile.

5.4 Summary and additional results

The chapter has extensively evaluated the performance of cooperative perception considering the baseline message generation rules. Its performance has been compared to the use of periodic generation policies, and the analysis showed that the baseline generation rules achieve an interesting balance between perception and communications performance when compared with periodic ones. However, the baseline generation rules present certain inefficiencies that can overload the communications channel and limit their scalability. The first inefficiency is related to the transmission of redundant information since multiple CAVs can detect the same object simultaneously and include its information on their CPMs. The second inefficiency is related to the generation of high number of CPMs with a small payload. These potential inefficiencies do not negatively impact on the perception. However, optimizing it further could improve the overall effectiveness of cooperative perception and the system’s scalability.

This chapter also performed a detailed analysis on cooperative perception. To this aim, the study demonstrates that cooperative perception can complement on-board sensors and increase the vehicle’s sensor perception beyond its sensors field of view. In particular, the study shows that very high perception levels can be achieved with penetration rates of only 40%, and the sensors’ characteristics do not greatly impact on the cooperative perception with a high market penetration rate. The results also show that the perception achieved with cooperative perception strongly depends on the sensors’ field of view and range when the market penetration rate is low. The study then shows that the perception achieved with cooperative perception degrades with high density and when sensor fusion is not implemented because these factors increase the channel load in the network and impact on the V2X communications performance.

This chapter also analyzed the impact of DCC on cooperative perception because it can alter the generation and transmission of CPMs and impact the effectiveness of cooperative perception. The study demonstrates that using congestion control only at the Access layer augments the latency (or information age) of CPMs. This negatively impacts connected automated driving that requires low latency for a safe driving. This study then demonstrates for the first time that this challenge can be addressed by combining the DCC functions at the Access and Facilities layers. This combination increases the perception and reduces the latency through the dynamic adaptation of the rate at which cooperative messages are generated and transmitted.

The evaluation presented in this chapter is a summary of the evaluation presented in the published articles [58] and [2] (included in Annex A.1 and Annex A.2), which perform additional evaluations on the dimensioning of cooperative perception. For example, the paper [58] (included in Annex A.1) presents additional metrics for the analysis conducted on cooperative perception message generation rules (Section 5.1). In particular, the paper presents the PDR metric computed at the radio level that once again justifies the results achieved by the baseline generation rules. The paper also reports the average time between updates which shows that the baseline generation rules provide updates nearly as frequently as the periodic policy at 10 Hz while better controlling the channel load. The work presented in [2] (included in Annex A.2) reports PDR at the radio level and application level for the evaluations performed in Section 5.2 and Section 5.3. These PDR further justify the achieved CBR and object perception ratio results presented in this thesis. In particular, the PDR computed at the application layer provides further insights to the impact of DCC because the packets dropped by DCC at the Access layer significantly degrade the PDR at the application level. Also, the paper analyzes the metric time between object updates, and demonstrates the variability in the time achieved between consecutive message updates. This metric reveals that there is higher variability in the time between consecutive updates when DCC is not applied due to the higher probability of consecutive packet losses due to collisions. However, with the Adaptive approach, the variability is lower when CAM and CPM have the same profile than when they have different profiles. These results show that DCC Access has an impact on the probability of receiving information about an object through CPMs.

6 Redundancy Mitigation

The high object redundancy generated by the baseline generation rules is one of the main inefficiencies reported from the analysis performed in Section 5.1. To address this problem, this chapter proposes a redundancy mitigation (a.k.a. redundancy control) technique to control the number of objects included in the CPM and reduce redundancy without affecting the achieved perception. To motivate in detail the need for redundancy mitigation, Section 6.1 first illustrates and quantifies the redundancy problem in cooperative perception considering the baseline generation rules. Then, Section 6.2 explains the proposed technique that extends the baseline generation rules to filter out the detected objects that have been recently transmitted by a nearby vehicle. In Section 6.3, a detailed analysis is carried out to compare the performance achieved with the proposed technique and the baseline generation rules. Finally, Section 6.4 concludes this chapter by providing a brief summary of the analysis performed in this chapter as well as a list of the details and additional results that can be found in the publications included in Annex A.3. The proposed technique can be considered as a natural extension of the baseline generation rules since it is also based on the mobility or dynamics of the objects. It has been presented and is part of the ETSI CPS Technical Report[1] [5].

6.1 Motivation

The problem of redundancy is illustrated considering the scenario in Figure 29 where an ego vehicle has 6 neighboring vehicles. Let's assume that all vehicles are equipped with a sensor that has a Field of View of 360º and move at 70 km/h. When baseline generation rules are applied in the network (defined in Section 3.4.2), all neighboring vehicles detect the ego vehicle and include it in the cooperative perception message every 300 ms. As a result, every vehicle receives 5 updates about the ego vehicle under every observation time window of 300 ms. Receiving redundant object updates in a sufficient number can be good to improve the detection accuracy and compensate possible packet loses. However, excessive and unnecessary redundancy increases the channel load and could negatively impact the V2X communication. Also, excessive redundancy significantly

[1] In ETSI's Technical Report the proposal RM algorithm is presented as dynamics-based redundancy mitigation technique.

increases the computing processing load at the receiver that has to process all the received information within a short period of time. This section evaluates and quantifies the effects illustrated in the example by means of simulations. In particular, the level of redundancy generated by the baseline generation rules is evaluated in detail to motivate the redundancy mitigation proposal. The analysis is performed in a highway scenario under medium and high traffic densities (see Section 4.2.1). By default, all vehicles are equipped with an ITS-G5 transceiver with 100% MPR and execute the baseline generation rules to generate CPMs. The evaluation is performed considering the 360º sensor configuration (see Section 4.1.2) and DCC is not activated in the considered scenarios.

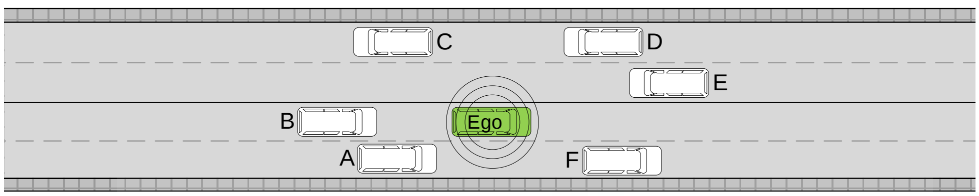
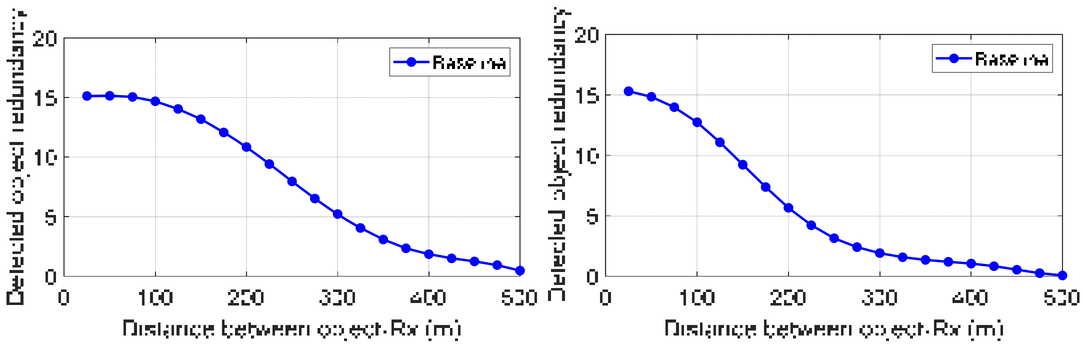


Figure 29. Example to illustrate the problem statement.

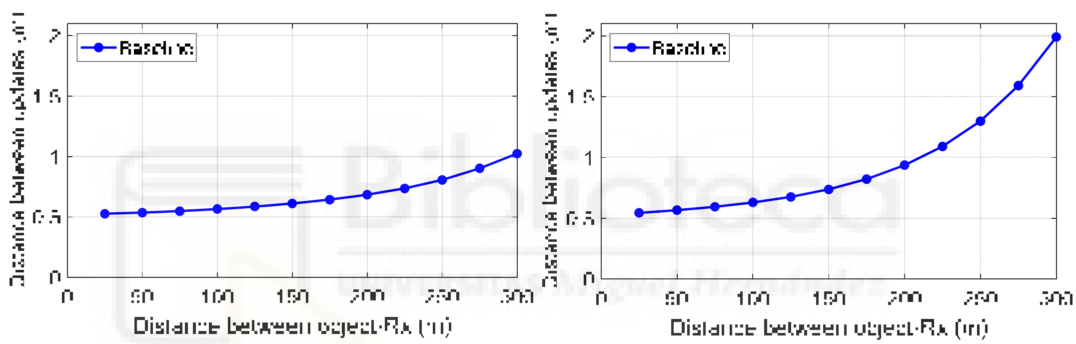
Figure 30 reports the detected object redundancy levels achieved by the baseline generation rules under the observation time window of 300 ms. The figure shows that, on average, vehicles receive around 15 updates for short distances and more than 12 updates for distances up to 100 m. This indicates that the vehicles were receiving updates about objects more frequently than really necessary. This is illustrated in Figure 31, which plots the distance traveled by an object between two successive CPMs that include information about that object. Figure 31 shows that, on average, this distance is lower than 1 m for distances between the object and the vehicle receiving the CPM below 200 m. This distance is increased up to 300 m for medium densities. This is in contrast to the 4 m threshold established by the CPM baseline generation rules to decide when an update should be transmitted. Sending frequent updates might be unnecessary from the perception point of view and can significantly increase the load on the communications channel. Reducing this unnecessary channel load could improve the performance of the cooperative perception. To this aim, a redundancy mitigation or control technique is proposed to modify the baseline generation rules to control the generated unnecessary object redundancy.



(a) Medium traffic density

(b) High traffic density

Figure 30. Detected object redundancy as a function of the distance between the detected object and the vehicle receiving the CPM



(a) Medium traffic density

(b) High traffic density

Figure 31. Average distance traveled by a detected object between two successive CPMs reporting about this object. Metric represented as a function of the distance between the object and the vehicle receiving the CPMs.

6.2 Proposal

The proposed redundancy mitigation technique extends the baseline generation rules to reduce the object redundancy without decreasing the perception capabilities of CAVs; it is referred to as RM in the rest of the chapter. RM considers the mobility or dynamics of the objects to remove an object from a CPM. More specifically, RM removes an object that satisfies the baseline generation rules in a CPM if the object's position or speed have not significantly changed since the last time the transmitting vehicle received information about this object in a CPM from any other vehicle. The objective is to avoid transmitting information about objects that has recently been included in CPMs by other vehicles since this information has probably been received by most of the nearby vehicles.

RM is executed after the baseline generation rules, and only when the baseline generation rules indicate that a new CPM must be generated. When executed, RM computes for every object that should be included in the CPM according to the baseline generation rules, the change in its absolute position (ΔP_R) and speed (ΔS_R) since the last time the object was received in a CPM transmitted by other vehicles. If $\Delta P\_R \leq P\_Threshold$ and $\Delta S\_R \leq S\_Threshold$, the object is not finally included in the CPM. Threshold values *P_Threshold* and *S_Threshold* must be configured equal or smaller than 4 m and 0.5 m/s, respectively, since these are maximum values of the baseline generation rules. The pseudo-code for this redundancy mitigation or control technique is shown in lines 14-21 of Algorithm II, and the process of the baseline generation rules is shown in lines 1-13 for completeness since the redundancy mitigation technique is executed after the baseline generation rules.

ALGORITHM II. REDUNDANCY MITIGATION PROPOSAL
Input: Detected objects
Output: Objects (if any) to include in CPM
Execution: Every *T_GenCpm*

```
1.  Set flag = false
2.  For every detected object do
3.    If the object is a new detected object then
4.      Include object in current CPM
5.      Set flag = true
6.    Else
7.      Calculate ΔP, ΔS and ΔT since the last time the object was included in a CPM
8.      If ΔP>4 m || ΔS>0.5 m/s || ΔT>1 s then
9.        Include object in current CPM
10.       Set flag = true
11.     End If
12.   End If
13. End For
14. If flag = true then
15.   For every detected object included in current CPM do
16.     Calculate ΔP_R and ΔS_R since last time the object was received in a CPM
17.     If ΔP_R < P_Threshold and ΔS_R < S_Threshold then
18.       Omit object from current CPM
19.     End if
20.   End For
21. End If
```


6.3 Performance analysis

The performance analysis presented in this section compares the baseline generation rules and the proposed RM technique. The proposed RM technique is evaluated considering *P_Threshold* =1 m, *S_Threshold*=0.5 m/s. The other simulation set-up and the configurations follows the same parameters adopted in Section 6.1.

6.3.1 Operation

The influence of RM on the CPM generation and the object inclusion are analyzed first. Table 9 shows the average number of CPMs generated per second per vehicle and the number of objects included in each CPM with the baseline generation rules and with RM. The table also reports the difference between the two algorithms. When compared with the baseline generation rules, RM reduces the CPM rate and the number of objects in each CPM for all traffic densities. This is because RM includes an object in the CPM only when its position or speed has significantly changed since the last time the transmitting vehicle received information about this object in a CPM. In particular, the number of objects in each CPM is significantly reduced (around 70% with high density and around 62% with medium density). The reduction is higher with high traffic density because with high density, a higher number of vehicles will report the same object and RM reduces more unnecessary redundant object information in the network. Following this trend, RM also reduces the number of CPMs transmitted per second. In particular, Table 9 shows that RM reduces the CPM rate significantly by around 26% and 30% for the medium and high density. These results clearly show that the RM proposal generates less CPMs per second with a smaller size than the current baseline generation rules.

Table 9. Average CPM rate and number of objects per CPM

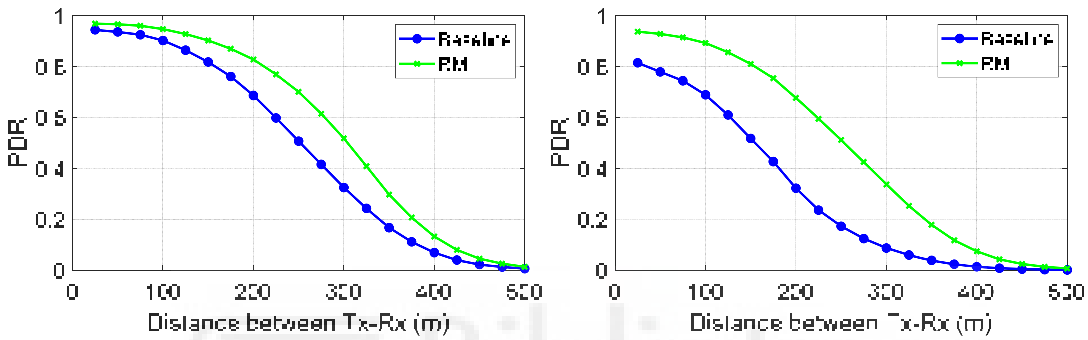
	CPM rate		**Number of objects**	
Techniques	**Medium**	**High**	**Medium**	**High**
Baseline	9.6Hz	9.6Hz	5.1	6.4
RM	7.1Hz	6.7Hz	1.9	1.9
Difference	-26.1%	-30.2%	-62.7%	-70.3

6.3.2 Communication performance

Reducing the CPM rate and CPM size reduces the channel load. This is illustrated in Table 10, which shows the average CBR for the proposal RM and the baseline generation rules under medium and high traffic densities. The table shows that a significant CBR reduction is observed with RM. In particular, RM reduces the CBR by around 40% for both traffic densities when compared to the baseline generation rules. Reducing the CBR and channel load reduces the packet collisions and improves the PDR. Figure 32 plots the PDR obtained with RM and baseline generation rules under both traffic densities. The results obtained show that the proposed RM achieves significantly higher PDR than the baseline generation rules. This PDR improvement is produced thanks to the reduction of the CBR shown in Table 10 with the proposed RM. The lowest PDR is achieved with the baseline generation rules. The PDR significantly degrades in the high density scenario because of its higher CBR and CPM generation rate.

Table 10. Average CBR

	Traffic Density	
Techniques	**Medium**	**High**
Baseline	49.4%	82.1%
RM	29.1%	49.0%
Difference	-41.1%	-40.3%

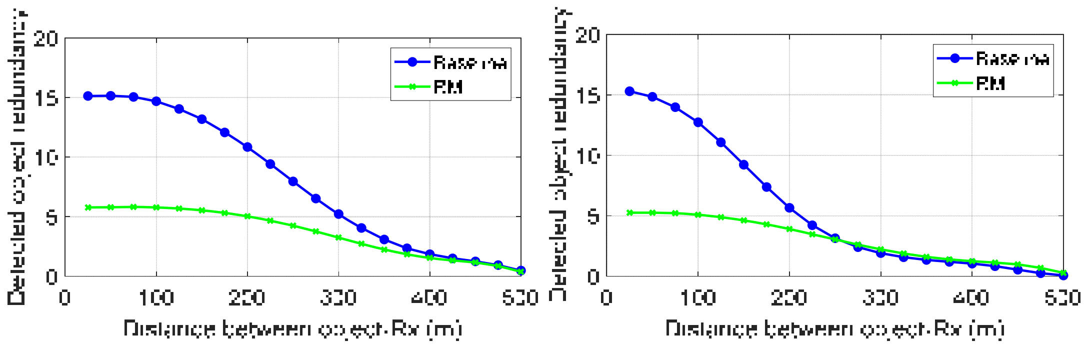


(a) Medium traffic density (b) High traffic density

Figure 32. PDR (Packet Delivery Ratio) as a function of the distance between transmitter and receiver under different densities.

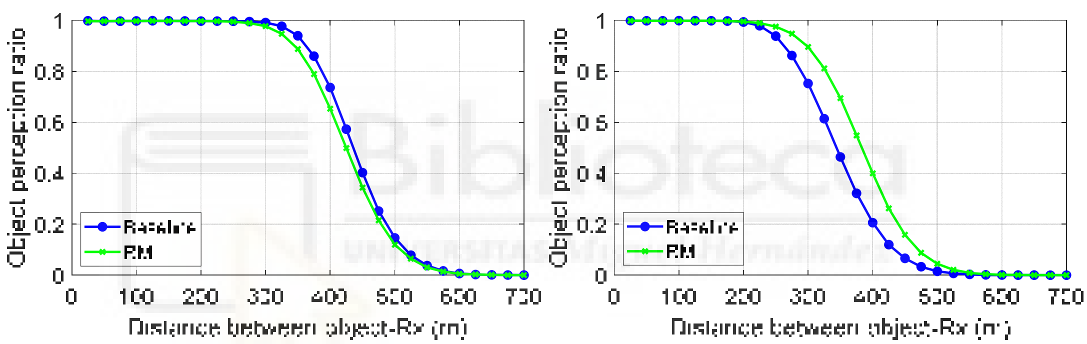
6.3.3 Redundancy and perception capabilities

Figure 33 shows the effectiveness of the RM proposal in terms of redundancy. In particular, the figure shows that RM significantly reduces the object redundancy to around 5 updates per observation window for distances up to around 200 m under both densities. This reduction is achieved without sacrificing the perception performance for short and medium distances that are critical for the safety of CAVs. This is illustrated in Figure 34 that compares the object perception ratio achieved with the current baseline generation rules and the RM proposal. The figure shows that RM achieves a high perception, similar to the baseline generation rules, for critical short and medium distances (up to around 200 m) under both densities. At larger distances, the perception decreases due to propagation and interference effects and the perception reported with RM achieves the same (or nearly the same) as baseline generation rules for the medium density. However, for the high density the perception is significantly increased with RM at larger distances. This is because the RM effectively controls the redundancy and reduces the CBR and improves the PDR. On the other hand, the baseline generation rules report a high CBR, which reduces the PDR (see Figure 32) and degrades the perception.



(a) Medium traffic density (b) High traffic density

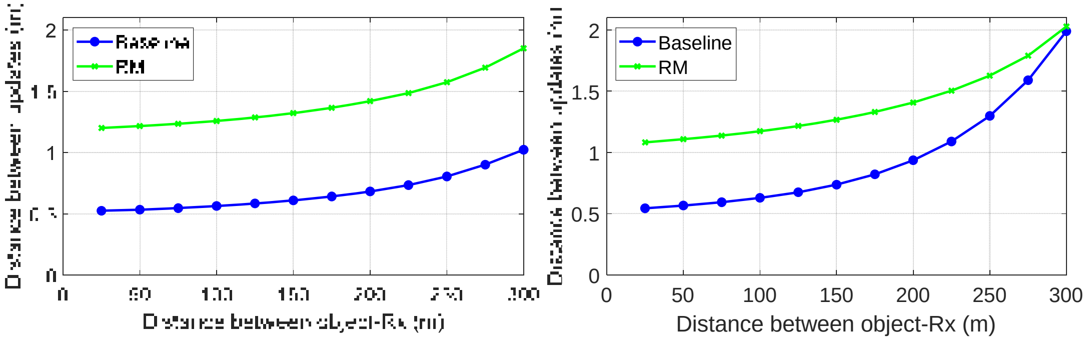
Figure 33. Detected object redundancy as a function of the distance between the detected object and the vehicle receiving the CPM.



(a) Medium traffic density (b) High traffic density

Figure 34. Object perception ratio as a function of the distance between the detected object and the vehicle receiving the CPM.

The perception achieved with the RM proposal is also analyzed in terms of how often a vehicle receives updates about a detected object. The updates can be received from any neighboring vehicle that has detected the same object. Figure 35 shows the average distance traveled by a detected object between two successive CPMs; the shortest the traveled distance, the more frequent a vehicle receives updated information about a detected object. The figure shows that both RM and the baseline generation rules report average location updates below 2 m for 200 m under all densities. This figure clearly shows that the RM proposal still provides frequent object updates, lower than the threshold (i.e., 4m) defined by the baseline generation rules, while achieving low CBR levels and high perception for critical short and medium distances.



(a) Medium traffic density

(b) High traffic density

Figure 35. Average distance traveled by a detected object between two successive CPMs reporting about this object. Metric represented as a function of the distance between the object and the vehicle receiving the CPMs.

6.4 Summary and additional results

This chapter addresses one of the main inefficiencies in the baseline generation rules defined by ETSI that generate significant detected object redundancy that can compromise the network scalability. To this aim, a redundancy mitigation technique is proposed in this chapter that extends the baseline generation rules to control the redundancy in the network. The evaluation results show that the redundancy mitigation technique significantly reduces the redundancy and channel load and improves the reliability of V2X communications. Also, the redundancy mitigation technique maintains the same perception performance (with significantly less messages) than the current baseline generation rules for safety-critical short and medium distances. It is also able to improve the perception at larger distances when the traffic density is high. The RM proposal achieves these results while still providing object updates below the threshold (i.e., 4 m) defined by the baseline generation rules.

The published article [64] (included in Annex A.3) extends the results of the proposed redundancy mitigation technique presented in this chapter by analyzing additional traffic densities and vehicle sensor configurations. The results obtained in [64] show that the redundancy mitigation technique can adapt to different configurations and improve the network scalability and the reliability of the V2X communications. Also, the paper analyzes different *P_Threshold* configuration values to evaluate the effectiveness of the proposed RM, and shows that the higher thresholds significantly reduce the redundancy to achieve low CBR levels. It is to be noted that the analysis presented in [64] derives the same conclusions as presented in this chapter. This once again justifies that the proposed redundancy mitigation technique works efficiently to reduce the redundancy under different scenarios and configurations without any impact on the perception. Also, [64] publishes additional metrics such as the PDF of the number of objects included in each CPM and the PDF of the number of CPMs generated per second, which provide additional insights on the operation of the proposed redundancy mitigation technique and the baseline generation rules.

7 Look-Ahead

The analysis performed in Section 5.2 revealed that the baseline generation rules defined by ETSI generate frequent cooperative perception messages that contain small number of objects, which is highly inefficient due to the resulting communications overhead. This chapter proposes a Look-Ahead (LA) technique to modify the baseline generation rules and reorganize the transmission of objects in less cooperative perception messages in order to reduce the overhead. This reorganization results in vehicles transmitting less messages, and each message includes information about a higher number of detected objects. To motivate the LA proposal, Section 7.1 first illustrates and quantifies in more detail the problem, explaining the inefficiency of the baseline generation rules related to the frequent generation of cooperative perception messages with small number of detected objects. Then Section 7.2 proposes and explains the LA technique that extends the current baseline generation rules to reorganize the transmission of objects in CPMs. In Section 7.3, a detailed analysis is carried out on the performance achieved with the LA and the baseline generation rules. Finally, Section 7.4 concludes this chapter by providing a brief summary of the analysis performed, as well as a list of the details and additional results that can be found in the publications included in Annex A.4. This Look-Ahead proposal has been presented at ETSI and is now part of the ETSI CPS technical report [5] as an extension of the baseline generation rules to generate CPMs.

7.1 Motivation

The problem is illustrated considering the scenario in Figure 36 where an ego vehicle has 6 neighboring vehicles. In this scenario we consider that the ego vehicle is equipped with a sensor that has a Field of View of 360º and that all vehicles move at 70 km/h. When the baseline generation rules are applied, the ego vehicle includes each detected vehicle in a CPM every 300 ms. Let's suppose a scenario where the ego vehicle detects for the first time all neighboring vehicles in a time interval $0 \leq \tau < 0.1$ s. In this scenario (Scenario 1), the ego vehicle generates one CPM every 300 ms, and each message includes the information of the 6 detected vehicles (Scenario 1 in Figure 36). It is though very unlikely that an ego vehicle can detect all its neighboring vehicles in the same time interval. In a more realistic scenario, vehicles constantly enter and exit the sensor detection range of an ego vehicle at different times. The ego vehicle will then include the detected objects (i.e., vehicles) in different messages. Let's consider in Scenario 2 that the ego vehicle detects two different neighboring vehicles in every time interval, thus detecting vehicles A and B in the interval $0 \leq \tau < 0.1$ s, vehicles C and D in $0.1 \leq \tau < 0.2$ s, and vehicles E and F in $0.2 \leq \tau < 0.3$ s. In this scenario, the ego vehicle ends up transmitting one CPM every 100 ms instead of every 300 ms like in Scenario 1. In Scenario 2, each message now includes information about 2 detected objects every 100 ms instead of 6 every 300 ms (Scenario 2 in Figure 36). Transmitting more CPMs per second consumes more bandwidth since each message includes the ITS PDU Header, the Management and Station Data containers. They occupy around 121 Bytes (see Table 3) and are shown in grey color in Figure 36. In addition, each CPM generates protocol headers from the Transport, Network, MAC (Medium Access Control) and PHY (Physical) layers. They occupy around 80 Bytes [2] and are shown in blue color in Figure 36. Figure 36 clearly shows that the transmission of more CPMs with information about less objects (Scenario 2) increases the signaling overhead compared to transmitting less CPMs that contain a larger number of objects (Scenario 1) [65].

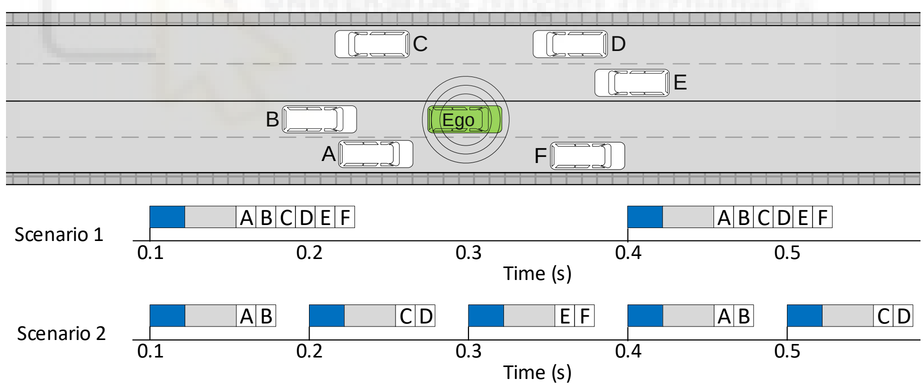
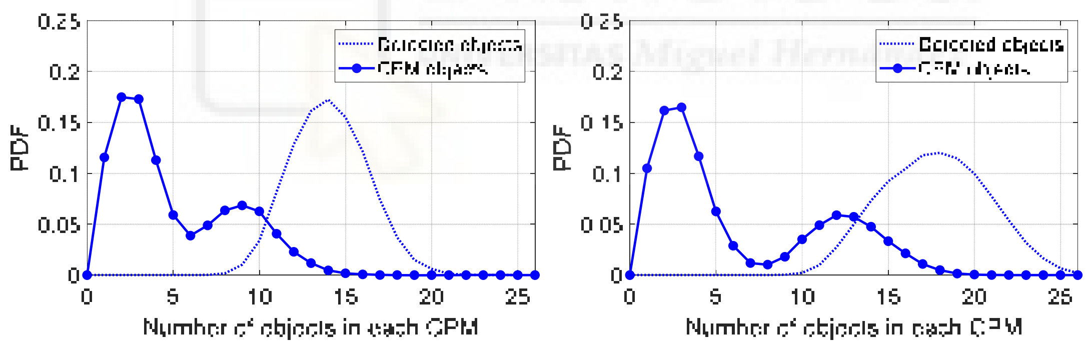


Figure 36. Example to illustrate the problem statement.

This section evaluates and quantify the effects illustrated in the example by means of simulations. The analysis is performed in a highway scenario under medium and high traffic densities (see Section 4.2.1). By default, all vehicles are equipped with an ITS-G5 transceiver with 100% MPR and execute baseline generation rules to generate the CPMs. Also, the evaluation is performed considering the 360º sensor configuration (see Section 4.1.2) and DCC is not activated in any of the considered scenarios.

The evaluation reports that, on average, the baseline generation rules generate CPMs at the rate of 9.6 Hz under both medium and high traffic density. These results reveal that messages are generated nearly every 100 ms independently of the traffic density. Figure 37 shows the PDF of the number of objects detected by each vehicle and the number of objects included in each CPM when considering the baseline generation rules. The obtained results show that the number of detected objects is non-negligible in both densities, and increases with the density. The obtained results also show that around 55%-58% of the CPMs contained 4 or less objects, and around 11% of the CPMs generated only contained 1 object for both densities. The obtained results demonstrate that the number of objects included in each CPM is significantly lower than the number of detected objects in the considered scenario. These results clearly confirm the problem previously described and illustrated in Figure 36 for realistic scenarios: the baseline generation rules generate frequent CPMs that contain a small number of detected objects. The transmission of frequent and small CPMs adds significant overhead. This overhead increases the channel load and can reduce the reliability of V2X communications, thus degrading the perception of the CAVs [65].



(a) Medium traffic density (b) High traffic density

Figure 37. PDF of the number of objects detected by each vehicle and included in each CPM with the baseline CPM generation rules.

7.2 Proposal

The Look-Ahead technique extends the current baseline generation rules to generate less frequent CPMs that contain a higher number of objects. Its goal is to reduce the amount of CPMs generated with information about a few detected objects in order to reduce the communications overhead generated by the protocol headers and the CPM header (around 200 Bytes in total). This is done without reducing the amount of information transmitted about the detected objects. To do so, the LA groups the information about the detected objects into a smaller number of CPMs of larger size. To this aim, LA is triggered every time a CPM must be generated by the baseline generation rules (e.g., because at least one object is included in the CPM or the last CPM was transmitted one second ago). Then, LA adds to this current CPM the objects that it predicts will be included in the next CPM. This prediction is made considering that the detected objects maintain their current acceleration. To this aim, the algorithm estimates the following parameters for the objects that do not currently satisfy the baseline generation rules:

$$Next\,\Delta P = \Delta P + S \cdot T\_GenCpm + 0.5 \cdot A \cdot T\_GenCpm^2 \tag{19}$$

$$Next\,\Delta S = \Delta S + A \cdot T\_GenCpm \tag{20}$$

$$Next\,\Delta T = \Delta T + T\_GenCpm \tag{21}$$

where *S* and *A* are the current speed and acceleration of the detected object. LA includes in the current CPM those detected objects that satisfy $Next\ \Delta P>4\ m$ or $Next\ \Delta S>0.5\ m/s$ or $Next\ \Delta T>1\ s$. When a detected object satisfies these conditions, its current information is included in the CPM (i.e., its current position, speed, etc.) and not the predicted one. Using LA, a CPM includes all the objects that currently satisfy the baseline generation rules and all the objects that are expected to satisfy the baseline rules in the next *T_GenCpm*. As a result, LA avoids that these objects generate a new CPM in the next *T_GenCpm*, and then reduces the number of generated CPMs of small size. It is also important to note that LA is robust against prediction errors resulting from the irregular movement of the detected objects since the worst-case prediction scenario will result in LA operating like the baseline generation rules. The pseudo-code for LA is shown in Algorithm III, where lines 1-13 correspond to the baseline generation rules (again for completeness) and lines 14-21 correspond to LA.

ALGORITHM III. LOOK-AHEAD PROPOSAL
Input: Detected objects
Output: Objects (if any) to include in CPM
Execution: Every *T_GenCpm*

1. Set *flag* = false
2. **For** every detected object **do**
3.   **If** the object is a new detected object **then**
4.   Include object in current CPM
5.   Set *flag* = true
6.   **Else**
7.   Calculate ΔP, ΔS and ΔT since the last time the object was included in a CPM
8.   **If** ΔP>4 m || ΔS>0.5 m/s || ΔT>1 s **then**

```
            Include object in current CPM
          Set flag = true
      End If
    End If
End For
If flag = true or last CPM was generated one second ago then
   For every detected object not included in current CPM do
      Calculate Next ΔP, Next ΔS and Next ΔT
      If Next ΔP>4 m || Next ΔS>0.5 m/s || Next ΔT>1 s then
           Include object in current CPM
      End if
   End For
End If
```

7.3 Performance analysis

The performance analysis conducted in this section compares the baseline generation rules and the proposed LA technique. The simulation set-up and the configurations adopt the same parameters used in Section 7.1.

7.3.1 Operation

This section first analyzes how the LA proposal influences the generation of CPMs. In particular, the impact on the CPM generation rate and the number of objects contained in each CPM are analyzed. Table 11 compares the average number of CPMs generated per second per vehicle and the number of objects (i.e., vehicles) per CPM with LA and with the baseline generation rules. The table also reports the difference between the two algorithms. Table 11 shows that LA reduces (between 35% and 44%) the number of CPMs generated per second compared to the baseline generation rules. This reduction is achieved by anticipating the transmission of information about detected objects and increasing the number of objects included in each CPM. Table 11 shows that LA augments (between 92% and 104%) the average number of objects included in each CPM when compared to the baseline generation rules [65].

Table 11. Average CPM rate and number of objects per CPM

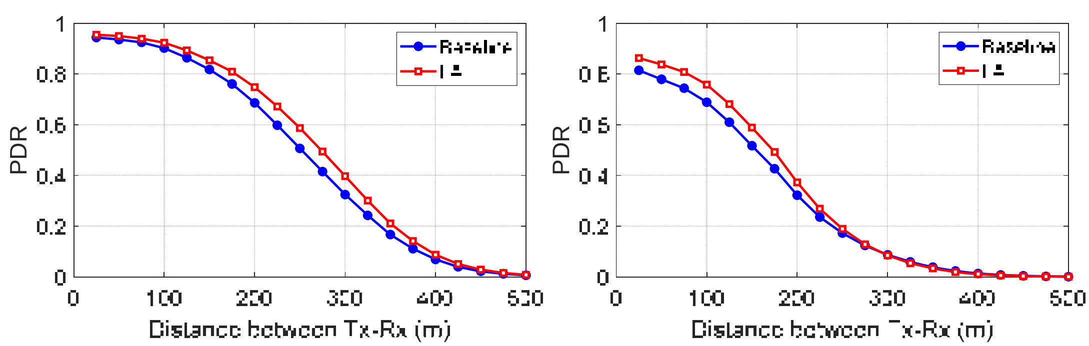
	CPM rate		Number of objects	
Techniques	**Medium**	**High**	**Medium**	**High**
Baseline	9.6	9.6	5.1	6.4
LA	5.4	6.2	10.4	12.3
Difference	-43.7%	-35.4%	104%	92.2%

7.3.2 Communication performance

The CPM transmission rate and size can significantly influence the channel load and can impact on the V2X communications performance. Table 12 shows that LA reduces the CBR for the medium density by around 16.2%. This reduction results from transmitting less CPMs and consequently reducing the communications overhead. With high density, both the CPM rate and the number of objects per CPM increases with LA when compared with medium density. This is because when new objects are detected, a CPM must be generated following the baseline generation rules. If LA does not add any additional object to this CPM, e.g. because they were included in the previous CPM, the CPM generated will only include the new detected objects (typically less than three objects per CPM in the considered scenario). This increases the CBR of LA resulting in a similar level than the baseline generation rules in the high density. However, Figure 38 shows that the LA proposal is able to improve the PDR compared to the baseline generation rules under both densities. This is mainly because LA significantly reduces the generation of communications overhead by reducing the CPM rate when compared with the baseline generation rules under both medium and high densities.

Table 12. Average CBR

Techniques	Traffic Density	
	Medium	**High**
Baseline	49.4%	82.1%
LA	41.4%	82.7%
Difference	-16.2%	0.7%

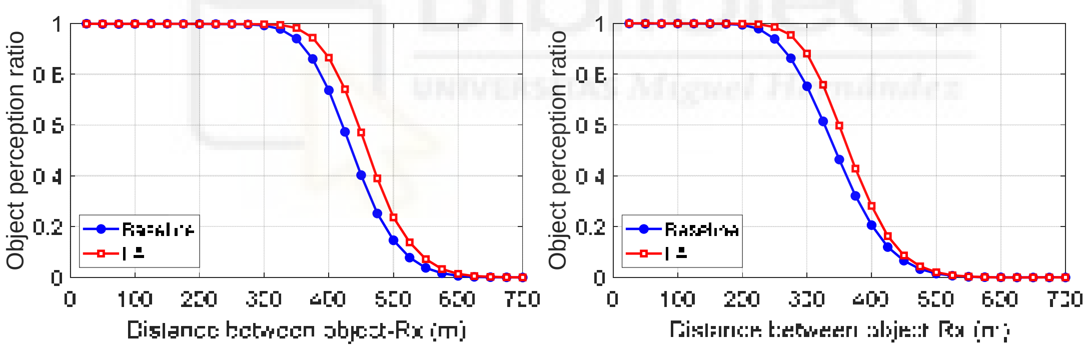


(a) Medium traffic density (b) High traffic density

Figure 38. PDR (Packet Delivery Ratio) as a function of the distance between transmitter and receiver under different densities.

7.3.3 Perception capabilities

The previous sections have shown that the LA proposal improves the V2X communications performance resulting from the reorganization of CPMs. This section evaluates how LA impacts the perception capabilities of CAVs. To this aim, Figure 39 compares the object perception ratio achieved with the current baseline generation rules and the LA proposal. The figure shows that LA and the baseline generation rules achieve high perception for distances up to around 300 m and 200 m for medium and high density. At larger distances, the perception achieved by LA is increased when compared with the baseline generation rules. This is due to two main reasons. The first one is the fact that LA increases the PDR and therefore the probability to correctly receive CPM messages increases. The second reason is that LA reorganizes the transmission of detected objects in CPMs. This reorganization results in a lower number of transmitted CPMs and an increase (between 13% and 41%) in the average number of times that a detected object is reported in a CPM. This also has a positive impact on the perception capabilities of CAVs and hence on the object perception ratio.

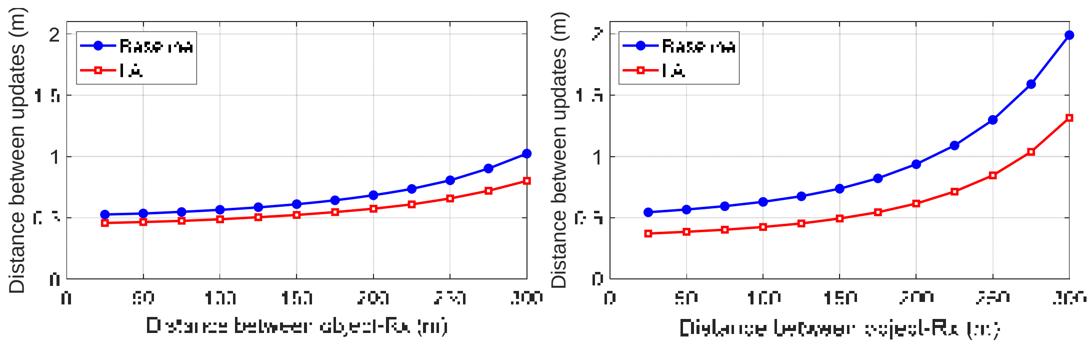


(a) Medium traffic density

(b) High traffic density

Figure 39. Object perception ratio as a function of the distance between the detected object and the vehicle receiving the CPM under different traffic densities.

The perception achieved with the LA proposal is also analyzed by computing the average distance traveled by a detected object between consecutive updates received by a vehicle. Figure 40 shows the average distance traveled by a detected object between two successive CPMs. The figure shows that LA provides the shortest traveled distance between updates. This is because it generates more frequent updates between the detected object and the vehicle receiving the CPMs. In fact, LA generates more frequent updates at larger distances and the difference is significant for the high density scenario. This once again shows that the LA proposal improves the perception of CAVs compared to the baseline generation rules.



(a) Medium traffic density

(b) High traffic density

Figure 40. Average distance traveled by a detected object between two successive CPMs reporting about this object. Metric represented as a function of the distance between the object and the vehicle receiving the CPMs.

7.4 Summary and additional results

This chapter addressed one of the main inefficiencies of the baseline generation rules, i.e. the generation of frequent CPMs, each with a few detected objects. This increases the communications overhead and degrades the V2X reliability as well as the perception capabilities due to the higher overhead. This thesis proposes overcoming this inefficiency with the Look-Ahead proposal that reorganizes the transmission of objects in CPMs. This reorganization results in vehicles transmitting less messages, and each message includes information about a higher number of detected objects. The evaluation results show that Look-Ahead is able to simultaneously reduce the overhead, and improve the reliability of V2X communications and the perception of CAVs. This is achieved by reorganizing the transmission and content of CPMs while still providing object updates less than the threshold (i.e., 4 m) defined by the baseline generation rules.

The published article in [65] (included in Annex A.4) extends the results presented in this chapter for the Look-Ahead technique. The paper analyzes the performance in urban and highway scenarios under different traffic densities. The evaluation in urban scenarios shows the impact of different vehicle mobility on cooperative perception and the results show that the LA still performs better than the baseline generation despite the strong impact of the buildings that significantly attenuate the radio signal and block the sensors field of view. The PDR results presented in the publication derives the same conclusions as presented in this chapter. Also, the metric average time between updates presented in the article derives the same conclusions and complements the average distance traveled by a detected object metric presented in this thesis. These additional results once again justify that the proposed Look-Ahead technique works efficiently under different scenarios and configurations to reduce the overhead, and improve the reliability of V2X communications and the perception of CAVs.

8 Scalable Cooperative Perception

Previous chapters proposed the so-called Look-Ahead and redundancy mitigation techniques to address the main inefficiencies identified in the baseline generation rules. Both proposals extend the baseline generation rules, and provide significant benefits in terms of perception and channel load. However, Look-Ahead and redundancy mitigation have been so far designed and evaluated independently while additional gains could be achieved if both techniques are adequately combined. In this context, this chapter investigates how Look-Ahead and redundancy mitigation could be combined to further improve cooperative perception and the system's scalability. Section 8.1 first performs an evaluation to show and quantify in more detail the inefficiencies of the standalone techniques (i.e., the baseline generation rules, look-ahead and redundancy mitigation techniques). Then, Section 8.2 proposes three different ways to combine the baseline generation rules with look-ahead and redundancy mitigation. The proposed solutions are evaluated in Section 8.3 without considering DCC, while Section 8.4 presents the evaluation with DCC. Finally, Section 8.5 concludes this chapter by providing a brief summary of the analysis performed as well as a list of the details and additional results that can be found in the publications included in [66]. The combinations presented in this chapter have been presented to ETSI[2].

8.1 Evaluation of standalone techniques

The combination of Look-Ahead and redundancy mitigation must be carefully configured since both techniques may have opposite effects on the generation of CPMs. For example, Look-Ahead generates larger CPMs by grouping objects into a smaller number of CPMs, but it can increase the amount of redundancy because objects can be transmitted more frequently than with the baseline CPM generation rules. On the other hand, redundancy mitigation techniques decrease the amount of redundancy, but can increase the frequent transmission of small CPMs. To quantify these inefficiencies, this section evaluates the operation and performance of the baseline generation rules, Look-

[2] These combination techniques are presented in the ETSI Technical Specification (TS 103 324) CPS drafting session meeting, ITSWG1(21)000009, 04 February 2021.

Ahead and the proposed redundancy mitigation technique separately. The goal is to highlight and quantify their inefficiencies when operating independently.

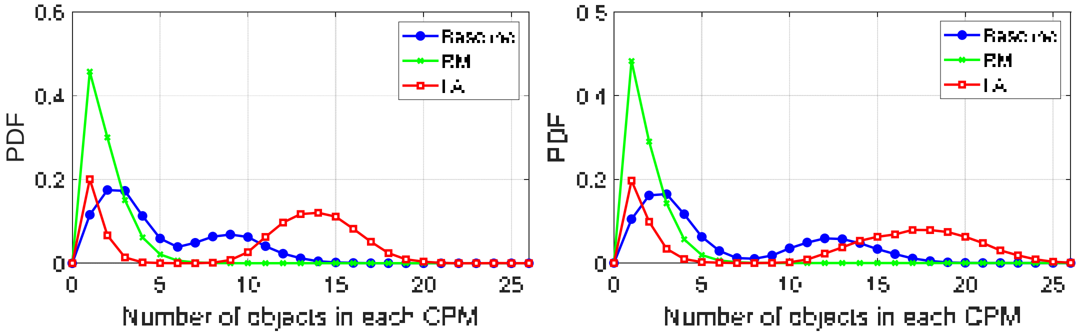
The analysis is performed in a highway scenario under medium and high traffic densities (Section 4.2.1). By default, all vehicles are equipped with an ITS-G5 transceiver with 100% MPR, with the 360º sensor configuration (see Section 4.1.2) and without DCC. The redundancy mitigation technique is evaluated considering the following thresholds: *P_Threshold* =1 m, *S_Threshold*=0.5 m/s.

Table 13 compares the channel load experienced with the baseline generation rules, the redundancy mitigation technique (RM in Table 13) and Look-Ahead (LA in Table 13). The CBR reduction with LA is achieved under medium traffic densities (16% reduction, respectively), as discussed in Section 7.3. This reduction is produced because LA groups the transmitted object information in larger and less frequent CPMs. As the traffic density increases, a higher number of new objects are detected per second, and this limits the capacity of LA to transmit larger CPMs by grouping detected objects. RM decreases even further the channel load compared to the baseline generation rules (between 41% and 45% under both traffic densities). This is the case because RM reduces the amount of information transmitted about detected objects to control the level of redundancy. Reducing the channel load decreases the interference and improves the reliability of V2X communications by decreasing the probability of packet collisions.

Table 13. Average CBR (Channel Busy Ratio)

Techniques	**Traffic density**	
	Medium	**High**
Baseline	49.4	82.1
RM	29.1	49
LA	41.4	82.7

Figure 41 plots the PDF (Probability Density Function) of the number of objects included in each CPM for the three techniques under evaluation. The figure clearly shows that RM increases the number of CPMs that contain a small number of objects compared to baseline generation rules and LA. In particular, around 97% of the CPMs generated by RM contain four or less objects, while this percentage is between 55% and 60% for baseline generation rules. These trends are observed for all traffic densities. Figure 41 also shows that LA can significantly increase the number of objects included in each CPM; only between 28% and 34% of CPMs contain information about four or less objects. Grouping the objects in larger CPMs was one of the design goals of LA in order to reduce the number of CPMs generated per second. Reducing the CPMs generated per second decreases the communications overhead resulting from protocol and CPM headers.

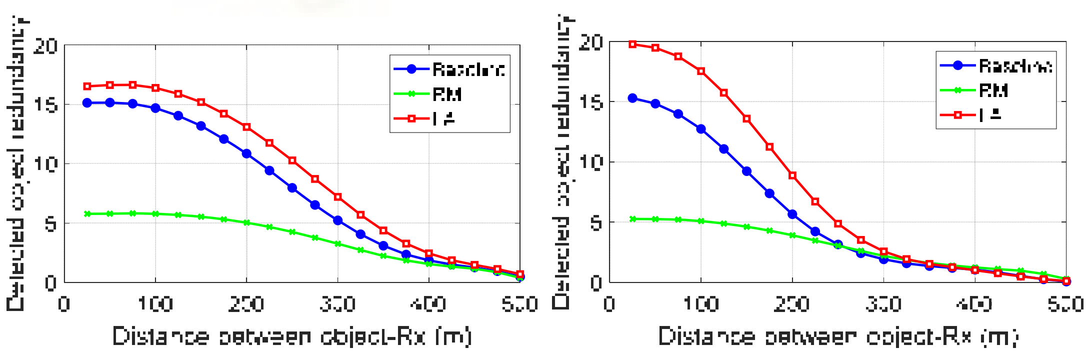


(a) Medium traffic density

(b) High traffic density

Figure 41. PDF of the number of objects included in each CPM.

The results depicted in Figure 42 show that RM is capable of significantly reducing the amount of redundancy while LA increases it compared to the baseline generation rules under all traffic densities. As previously discussed, some redundancy may be positive to, for example, combat packet losses. However, excessive and unnecessary redundancy increases the channel load and computing processing load at the receiver, which will have to process all the received information.



(a) Medium traffic density

(b) High traffic density

Figure 42. Detected object redundancy as a function of the distance between the detected object and the vehicle receiving the CPM.

This section has analyzed the operation and performance of each of the three techniques under evaluation when operating independently. The evaluation has shown that the baseline generation rules generate high channel load and redundancy levels. Redundancy and channel load can be reduced with the redundancy mitigation technique. However, this technique generates a high number of CPMs with a small number of objects that produce communications overhead and utilize inefficiently the communications channel. Look-Ahead is effective in reducing the number of CPMs with small number of objects, but this is achieved at the cost of increasing the redundancy levels. This analysis clearly highlights that each technique has advantages but also inefficiencies, and next section studies how the techniques can be combined for higher effectiveness.

8.2 Combination of Look-Ahead and Redundancy Mitigation

This section proposes three ways to combine the baseline generation rules with RM and LA. To better understand how each combination generates CPMs, Figure 43 first shows how the baseline generation rules, RM and LA select the detected objects to be included in a CPM using an illustrative example. The example considers a scenario where a transmitting vehicle detects 25 objects, but only 6 out of the 25 detected objects satisfy the baseline generation rules. In this case, only these 6 objects would be included and transmitted in the current CPM when using the baseline generation rules (Figure 43a). Let's now consider that the RM identifies 10 out of the 25 detected objects as redundant[3], i.e., their position or speed have not significantly changed since the last time the transmitting vehicle received information about them in a CPM from any other vehicle. Out of these 10 redundant objects, it is considered in the example that only 2 of them currently satisfy the baseline generation rules. If redundancy mitigation is applied, these 2 objects are removed from the CPM and only the remaining 4 objects that currently satisfy the generation rules are included in the current CPM as illustrated in Figure 43b. It should be noted that RM is only applied to the objects that currently satisfy the baseline generation rules since the other objects will not be included in the current CPM anyway. However, Figure 43b marks the 10 objects identified as redundant for illustration purposes. The example also considers that 3 of the detected objects that currently do not satisfy the baseline generation rules will satisfy them in the next *T_GenCpm*. In this case, these 3 detected objects will be included in the current CPM together with the 6 objects

[3] These 10 redundant objects are highlighted in Figure 43a, Figure 43b and Figure 43c for illustration purposes, but the baseline generation rules and LA do not take into account if an object is redundant or not to include it in the CPM.

that currently satisfy the CPM generation rules if LA is applied (Figure 43c). Figure 43 clearly illustrates how each of the techniques under evaluation generate different CPMs when applied individually.

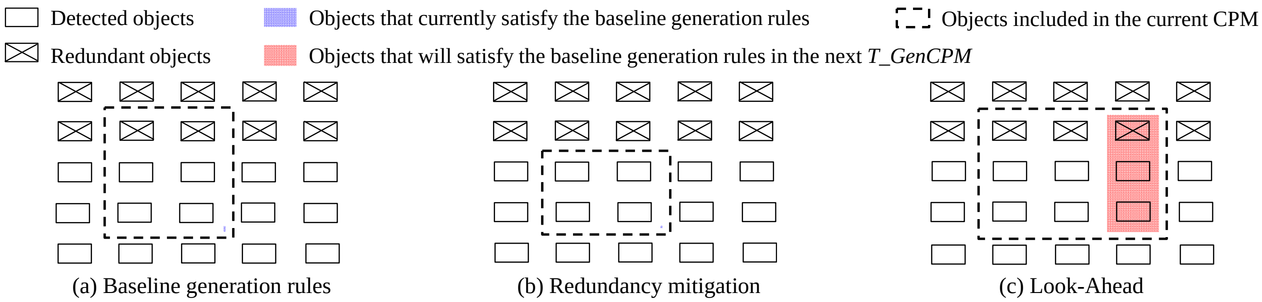


Figure 43. Example that illustrates how the baseline generation rules, RM and LA build their CPMs when applied individually.

8.2.1 LARM

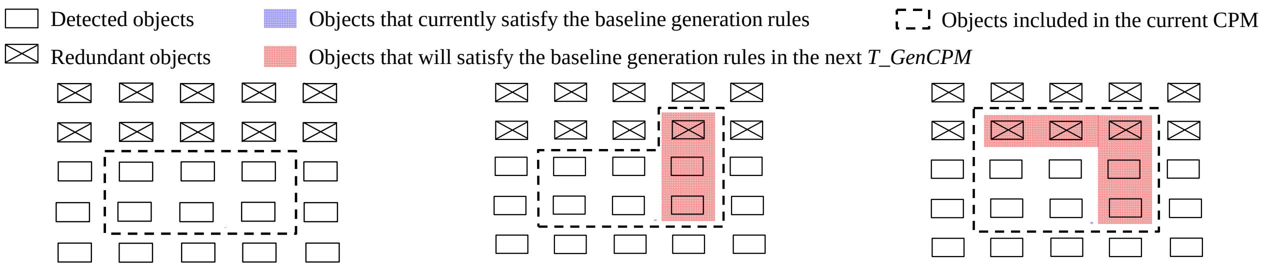
The first proposal to combine LA and RM is referred to as LARM. It first applies the baseline generation rules and LA, and then applies RM to the objects selected by the baseline generation rules and LA. As a consequence, LARM removes from the CPM all the objects that are considered redundant even though they were selected for inclusion by the baseline generation rules or LA. The objective is to reduce the redundancy generated by LA, and also to benefit from the reduction in channel load achieved with RM.

LARM operates as follows. Every *T_GenCpm*, the baseline generation rules are applied first. As a result, all the objects that satisfy ΔP>4m or ΔS>0.5m/s or ΔT>1s are selected for inclusion in the currently generated CPM (lines 1-13 of Algorithm IV). If a CPM is going to be generated, e.g., because at least one object is selected for inclusion with the baseline generation rules, LA is applied (lines 14-21 of Algorithm IV) and all the objects that were not initially selected by the baseline generation rules but that satisfy *Next* ΔP>4m or *Next* ΔS>0.5m/s or *Next* ΔT>1s are selected by LA for inclusion in the currently generated CPM. Then, RM is applied to all the objects selected for inclusion in the current CPM by the baseline generation rules or by LA (lines 22-29 of Algorithm IV). To this aim, RM computes the change in absolute position (*ΔP_R*) and speed (*ΔS_R*) of each object since the last time they were received in a CPM from other vehicles. All the objects that satisfy *ΔP_R≤P_Threshold* and Δ*S_R*≤ *S_Threshold* are removed from the current CPM. This affects the objects that satisfy the baseline generation rules in the current *T_GenCpm* and the objects that satisfy the baseline generation rules in the next *T_GenCpm*.

ALGORITHM IV. LARM
Input: Detected objects
Output: Objects (if any) to include in CPM
Execution: Every *T_GenCpm*

```
Set flag = false
For every detected object do
  If the object is a new detected object then
    Include object in current CPM
    Set flag = true
  Else
    Calculate ΔP, ΔS and ΔT since the last time the object was included in a CPM
    If ΔP>4 m || ΔS>0.5 m/s || ΔT>1 s then
      Include object in current CPM
      Set flag = true
    End If
  End If
End For
If flag = true then
  For every detected object not included in current CPM do
    Calculate Next ΔP, Next ΔS and Next ΔT
    If Next ΔP>4 m || Next ΔS>0.5 m/s || Next ΔT>1 s then
      Include object in current CPM
    End if
  End For
End If
If flag = true then
  For every detected object included in the current CPM do
  Calculate ΔP_R and ΔS_R since last time the object was received in a CPM
    If ΔP_R < P_Threshold && ΔS_R < S_Threshold then
      Omit object in current CPM
    End If
  End For
End If
```

Figure 44a illustrates the operation of LARM, and how it selects the objects to be included in a CPM using the example in Figure 43. In the example, a transmitting vehicle detects 25 objects, but only 6 of them currently satisfy the baseline generation rules. Additionally, 3 detected objects that do not currently satisfy the baseline generation rules will do so in the next *T_GenCpm*. LARM applies then RM to the 9 objects that satisfy the generation rules now and in the next *T_GenCpm*. 3 out of these 9 objects are detected as redundant by RM and removed from the CPM. In Figure 44a, RM removes the objects initially selected by the baseline generation rules and objects selected by LA. As a result, LARM finally includes 6 detected objects in the current CPM.



(a) LARM (b) RMLA (c) *e*RMLA

Figure 44. Example that illustrates how each proposal to combine the baseline generation rules, RM and LA builds their CPMs.

8.2.2 RMLA

The second proposal to combine LA and RM is referred to as RMLA. It first applies the baseline generation rules and RM, and then LA. As a result, RM removes first the objects that currently satisfy the baseline generation rules but are considered redundant. Then, LA is applied to the objects that do not currently satisfy the baseline generation rules (i.e., LA is not applied to the ones included in the current CPM nor the ones that have been removed by RM). By applying LA after the baseline generation rules and RM, RMLA anticipates the transmission of as many objects as possible in the current CPM, but omits the ones currently considered redundant by RM. However, RMLA can anticipate the transmission of objects that may be deemed redundant because it applies LA after RM. This is one of the main differences with LARM that applied RM last and then removed all objects deemed redundant from the list of objects selected by the baseline generation rules and LA. We should note that RMLA avoids the transmission of a CPM if it only contains redundant objects, because LA is only applied if at least one selected object is not redundant.

RMLA operates as follows. Every *T_GenCpm*, the baseline generation rules are executed first (lines 1-13 of Algorithm V) and all objects that satisfy ΔP>4 m or ΔS>0.5 m/s or ΔT>1 s are selected for inclusion in the currently generated CPM. RM is then applied only to the list of selected objects, and removes from this list those objects that are deemed redundant because they satisfy $\Delta P\_R \leq P\_Threshold$ and $\Delta S\_R \leq S\_Threshold$ (lines 14-24 of Algorithm V). If at least one object is still selected for inclusion in the current CPM, LA is executed (lines 25-32 of Algorithm VI) to all the objects that are currently not included in the CPM and that have not been removed by RM.

ALGORITHM V. RMLA
Input: Detected objects
Output: Objects (if any) to include in CPM
Execution: Every *T_GenCpm*

```
Set flag = false
For every detected object do
    If the object is a new detected object then
        Include object in current CPM
        Set flag = true
    Else
        Calculate ΔP, ΔS and ΔT since the last time the object was included in a CPM
        If ΔP>4 m || ΔS>0.5 m/s || ΔT>1 s then
            Include object in current CPM
            Set flag = true
        End If
    End If
End For
If flag = true then
    For every object included in the current CPM do
        Calculate ΔP_R and ΔS_R since last time the object was received in a CPM
        If ΔP_R < P_Threshold && ΔS_R < S_Threshold then
            Omit object in current CPM
        End If
    End For
    If current CPM does not contain any object then
        Set flag = false
    End If
End if
If flag = true then
    For every detected object not included in current CPM and not removed by RM do
        Calculate Next ΔP, Next ΔS and Next ΔT
        If Next ΔP>4 m || Next ΔS>0.5 m/s || Next ΔT>1 s then
            Include object in current CPM
        End if
    End For
End If
```

Figure 44b illustrates the operation of RMLA and how it selects the objects to be included in a CPM. In this example, 25 objects are currently detected but only 6 of them satisfy the baseline generation rules. Additionally, 3 objects satisfy the baseline generation rules in the next *T_GenCpm* and are thus added by LA to the current CPM. The differences between RMLA and LARM can be clearly observed by comparing Figure 44a and Figure 44b. With LARM (Figure 44a), part of the objects anticipated by LA were removed by RM. However, with RMLA (Figure 44b), RM is only applied to the objects that currently satisfy the baseline generation rules, but not to the objects anticipated by LA. As a result, all 3 objects anticipated by LA are included in the CPM generated by RMLA.

8.2.3 *e*RMLA

The third proposal to combine LA and RM is an extension of RMLA, and is referred to as *e*RMLA. This extension is designed with two goals. The first one is to avoid the transmission of a CPM if it only contains redundant objects, i.e., when all the objects that satisfy the baseline generation rules are redundant. When this happens, *e*RMLA behaves as RM and RMLA and does not generate a CPM. The second goal is to include as many objects as possible in the CPM when a CPM has to be generated (e.g., when at least one object satisfies the baseline generation rules and is not redundant). When this occurs, *e*RMLA behaves as LA and includes all the objects removed by RM plus the ones anticipated by LA.

To achieve its goals, *e*RMLA first applies the baseline generation rules and then RM in order to remove all the objects included in the current CPM that are considered redundant (like in RMLA). If all the objects are removed, then the CPM is not generated. However, if at least one object satisfies the baseline generation rules and is not removed by RM, *e*RMLA applies LA to all detected objects, including those removed by RM. This is in contrast to RMLA that applies LA to all detected objects except those removed by RM. This is an important difference because all objects removed by RM currently satisfy the baseline generation rules. Therefore, when *e*RMLA applies LA to these objects, LA predicts that they will also satisfy the baseline generation rules in the next *T_GenCpm*. This is the case because e.g., the distance traveled since the last time these objects were included in a CPM increases with time. In this context, LA in *e*RMLA will anticipate their transmission in the current CPM. The only objects removed by RM that will not be anticipated by the original LA are the new detected objects. This is the case because LA is able to anticipate only the transmission of objects that have been already transmitted in a previous CPM. *e*RMLA modifies the original LA technique so that it can also anticipate in the current CPM the new detected objects that have been removed by RM. To this aim, one extra condition is added to LA when executed in *e*RMLA: if the object is new (i.e., an object that the vehicle has not transmitted before), it is included in the CPM.

*e*RMLA operates as follows. The baseline generation rules are first executed to identify and select for inclusion in the current CPM the detected objects that satisfy ΔP>4 m or ΔS>0.5 m/s or ΔT>1 s (lines 1-13 of Algorithm VI). Then, RM removes from the CPM the objects that are considered redundant (i.e., that satisfy $\Delta P\_R \leq P\_Threshold$ and $\Delta S\_R \leq S\_Threshold$) as specified in lines 14-23 of Algorithm VI. If all objects are removed, the CPM is not generated. When a CPM must be generated (e.g., because at least one object is included in the CPM after applying RM), *e*RMLA triggers LA (lines 25-35 of Algorithm VI). LA anticipates and includes in the current CPM the detected objects that satisfy *Next* ΔP>4m or *Next* ΔS>0.5m/s or *Next* ΔT>1s. LA also includes in the current CPM the new detected objects that were included by the baseline generation rules but removed by RM (lines 31-33 of Algorithm VI).

ALGORITHM VI. *e*RMLA
Input: Detected objects
Output: Objects (if any) to include in CPM
Execution: Every *T_GenCpm*

```
1.  Set flag = false
2.  For every detected object do
3.    If the object is a new detected object then
4.      Include object in current CPM
5.      Set flag = true
6.    Else
7.      Calculate ΔP, ΔS and ΔT since the last time the object was included in a CPM
8.      If ΔP>4 m || ΔS>0.5 m/s || ΔT>1 s then
9.        Include object in current CPM
10.       Set flag = true
11.     End If
12.   End If
13. End For
14. If flag = true then
15.   For every object included in the current CPM do
16.     Calculate ΔP_R and ΔS_R since last time received in a CPM
17.     If ΔP_R < P_Threshold && ΔS_R < S_Threshold then
18.       Omit object in current CPM
19.     End If
20.   End For
21.   If current CPM does not contain any object then
22.     Set flag = false
23.   End If
24. End if
25. If flag = true then
26.   For every detected object not included in current CPM do
27.     Calculate Next ΔP, Next ΔS and Next ΔT
28.     If Next ΔP>4 m || Next ΔS>0.5 m/s || Next ΔT>1 s then
29.       Include object in current CPM
30.     End if
31.     If the object is a newly detected object then
32.       Include object in current CPM
33.     End If
34.   End For
35. End If
```

Figure 44c illustrates the operation of *e*RMLA and the objects it selects for inclusion in the current CPM using the same example. The figure shows that RM removes two objects from the CPM, i.e., it removes 2 out of 6 detected objects that currently satisfy the baseline generation rules. Since RM does not remove all objects, the CPM must be generated, and LA is applied next. LA anticipates 3 additional detected objects that satisfy the baseline generation rules in the next *T_GenCpm*, plus the 2 objects initially removed by RM. As a result, the CPM generated contains 9 objects in total. The CPM generated in Figure 44c is equal to the CPM generated by LA alone (see Figure 43c). However, it is important to note that this might not be the case for all CPMs. With *e*RMLA, LA is not triggered if RM removes all the objects that currently satisfy the baseline generation rules. If this is the case, then a CPM is not generated. The objective sought with RM in *e*RMLA is to reduce the number of CPMs generated per second and increase their size compared to when using LA alone.

8.3 Evaluation of the combined techniques

This section analyzes and compares the performance of the proposed techniques to combine LA and RM with the baseline generation rules. This first analysis is conducted without including congestion control since congestion control can influence the techniques under evaluation, and it is important to first understand well how the techniques behave before considering any additional influences.

8.3.1 Generation of CPMs

We first analyze how the proposed combined techniques influence the generation of CPMs and the inclusion of objects in CPMs. To this aim, Table 14 and Table 15 report the average rate of CPMs generated per second per vehicle and the number of objects included in each CPM, respectively. The results obtained show that *e*RMLA achieves the lowest rate of CPMs for all traffic densities. This is the case because *e*RMLA includes in a CPM all objects that satisfy the baseline generation rules at the time the CPM is generated as well as those that satisfy them in the next *T_GenCpm*. In addition, *e*RMLA does not omit any redundant object from the CPM when it is generated. This operation has two main effects. First, *e*RMLA increases the size of CPMs and decreases the probability of generating CPMs with a small number of objects. The second effect is that after generating a CPM, *e*RMLA generally does not generate another CPM in the next

T_GenCpm since most of the detected objects are already included in the current CPM. This is partly visible in Table 15 that shows that *e*RMLA results in the highest average number of objects included in a CPM, even higher than the number of objects included by LA when applied alone.

Table 14 also shows that LARM and RMLA generate more CPMs per second than *e*RMLA. This is the case because LARM and RMLA do not effectively control the number of CPMs that contain a small number of objects (see Table 15). When LARM and RMLA are applied, RM removes the redundant objects that satisfy the baseline generation rules at the time of generating a CPM. This reduces the number of objects included in the current CPM, and can trigger the generation of a new CPM in the next *T_GenCpm*. This is because in the next *T_GenCpm*, one (or more) of these removed objects may not be redundant anymore and should hence be transmitted in a CPM. This is confirmed by Table 15 that shows that LARM and RMLA result in a lower average number of objects included in each CPM than *e*RMLA. Generating many CPMs with a small number of objects is highly inefficient since most of the CPM will be (protocol and CPM) headers.

Table 14. Average rate of CPMs generated per second

Techniques	**Traffic density**	
	Low	**High**
Baseline	9.6Hz	9.6Hz
RM	7.1Hz	6.7Hz
LA	5.4Hz	6.2Hz
LARM	6.4Hz	6.1Hz
RMLA	5.4Hz	5.1Hz
*e*RMLA	2.6Hz	2.1Hz

Table 15. Average number of objects included in each CPM

Techniques	**Traffic density**	
	Low	**High**
Baseline	5.1	6.4
RM	1.9	1.9
LA	10.4	12.3
LARM	2.2	2.1
RMLA	3.4	3.2
*e*RMLA	13.8	17.4

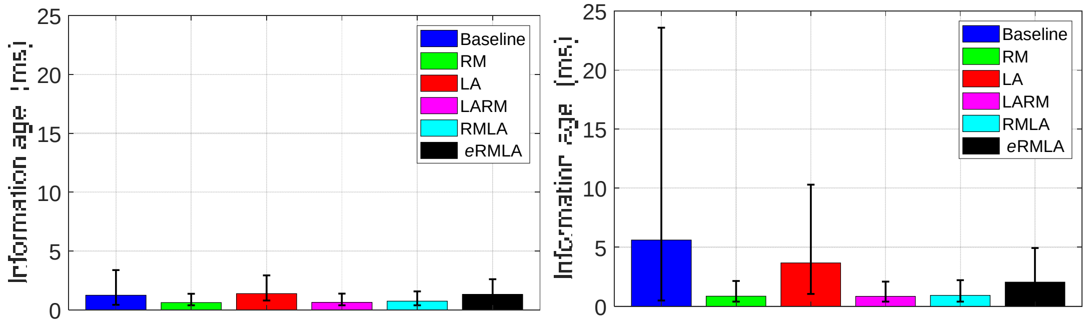
8.3.2 V2X communications

The CPM transmission rate and size can significantly influence the channel load and hence the V2X communications performance. Table 16 presents the average CBR experienced with each technique under both traffic densities. The results obtained show that all the proposed combined techniques reduce the channel load when compared with existing standalone techniques (baseline generation rules, RM and LA). This is the case because the combined techniques are able to reduce the average CPM generation rate and the number of objects included in each CPM, as discussed in the previous section. All three proposals reduce the CBR with *e*RMLA achieving the lowest CBR.

Table 16. Average CBR (Channel Busy Ratio)

Techniques	**Traffic Density**	
	Medium	**High**
Baseline	49.4%	82.1%
RM	29.1%	49.0%
LA	41.4%	82.7%
LARM	27.3%	46.0%
RMLA	25.8%	43.0%
eRMLA	24.4%	42.0%

It is important for the effectiveness of cooperative perception that vehicles exchange the sensed data with minimum latency. Figure 45 represents the information age obtained for all the techniques and traffic densities. The information age is defined as the difference between the time the CPM is generated and the time the CPM has been received. The bars in the figure represent the mean values and the vertical lines correspond to the 5th and 95th percentiles. The information age is highly influenced by the channel access mechanism and the channel load. On the other hand, the distance between transmitter and receiver does not have a significant impact on the information age because the propagation delay can be considered negligible. Figure 45 shows that the information age is below 4 ms for all techniques under medium traffic densities. For the high-density scenario, the information age increases with the baseline generation rules and LA because they generate higher channel load levels. The average information age is still around 5 ms with high traffic densities, but some CPMs were delayed between 10 ms and 25 ms. Figure 45 shows that *e*RMLA results in a slightly higher information age compared to LARM and RMLA because it generates significantly larger messages (Table 15).



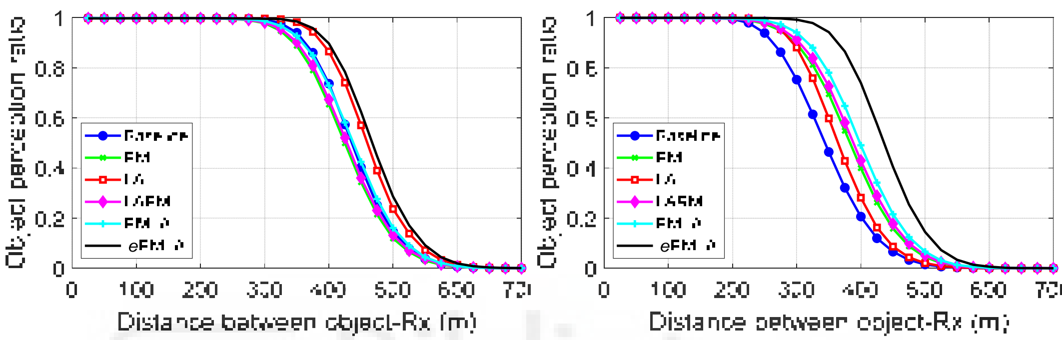
(a) Medium (b) High

Figure 45. Average information age of CPMs for all traffic densities. The bars represent the average values and the vertical lines represent the 5th and 95th percentiles**.**

8.3.3 Perception

The perception level achieved depends on how objects are organized and included in CPMs as well as on the channel load. Figure 46 plots the object perception ratio obtained with the different techniques under all traffic densities under evaluation. In the medium traffic density scenario (Figure 46a), all the techniques achieve a very high object perception ratio up to around 300 m even though the proposed combined techniques approximately reduce by half the channel load compared with the baseline generation rules and LA. This is the case because the proposed combined techniques more effectively use the radio channel by reducing the transmitted overhead and redundancy. For larger distances, the object perception ratio decreases due to propagation and interference effects, and the highest object perception ratio is obtained with *e*RMLA and LA. LA achieves a high perception despite its high channel load because of its high transmission efficiency (more transmitted information about objects and less overhead). The highest perception level is obtained with *e*RMLA because it is able to achieve a higher transmission efficiency, and reduce the redundancy compared to LA, thus reducing the channel load. When the traffic density augments (Figure 46b), the object perception ratio decreases in general because the channel load and interferences increase. For all the techniques, the object perception ratio is still very high up to 200 m for the high density (Figure 46). The lowest perception is experienced with the baseline generation rules given its inherent inefficiencies that result in the highest CBR (Table 16). The highest degradation in the perception due to the increase of the traffic density is experienced by LA because a higher number of new objects are detected per second, and the capacity of LA to group detected objects is more limited (see Section 7 for details).

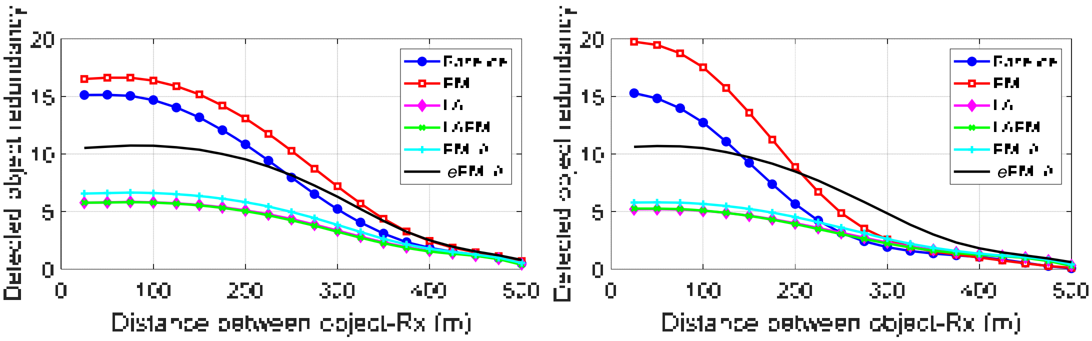
Figure 46 shows that *e*RMLA achieves the highest perception levels for all traffic densities because it is able to maintain a high transmission efficiency, and relatively low redundancy and channel load. The results obtained demonstrate its good scalability since the object perception ratio obtained with *e*RMLA is nearly maintained when the traffic density increases. The conducted evaluation shows that *e*RMLA is the technique that achieves the highest object perception ratio (Figure 46) and the lowest channel load (Table 16). This is the case because *e*RMLA is able to reduce redundancy while most of the CPMs generated include all detected objects and nearly no small CPMs are generated.



(a) Medium (b) High

Figure 46. Object perception ratio as a function of the distance between the detected object and the vehicle receiving the CPM under different traffic densities.

*e*RMLA achieves the highest object perception ratio due to its capacity to maintain adequate redundancy levels while generating the lowest channel load. Figure 47 shows the detected object redundancy achieved with all the techniques for all the traffic densities evaluated. These results demonstrate that the three techniques proposed (LARM, RMLA and *e*RMLA) are able to significantly reduce the redundancy compared to the baseline generation rules and LA. The lowest redundancy levels are achieved by RM, LARM and RMLA, but they generate higher load and transmit less efficiently, i.e., generate smaller CPMs (Table 15). *e*RMLA increases the redundancy when compared with LARM, RMLA and RM, but maintains a lower CBR (Table 16). When compared with the baseline generation rules and LA, *e*RMLA achieves low redundancy levels at short distances and high redundancy at larger distances. Increasing the redundancy levels at high distances increase the probability of successfully receiving the CPMs and augments then the object perception ratio at high distances.



(a) Medium (b) High

Figure 47. Detected object redundancy as a function of the distance between the detected object and the vehicle receiving the CPM under different traffic densities

8.4 Evaluation with congestion control

This section evaluates the performance achieved with the combined techniques when considering the impact of congestion control. In particular, this study considers the DCC framework and the impact of DCC Access and DCC Facilities. This evaluation focuses on the high traffic density scenario that generates the highest channel load levels and activates DCC. The evaluation in Section 8.4.1 considers that only CPMs are transmitted in the channel, while Section 8.4.2 considers that the transmission of CAMs and CPMs share the same radio channel.

8.4.1 Only CPMs

Table 17 shows different metrics to understand the effect of DCC on the proposed techniques and the baseline generation rules. In particular, the table shows the average CBR, the average rate of CPMs generated per second by the collective perception service (column CPM Gen), the average rate of CPMs that are effectively transmitted per second to the radio channel (column CPM Tx), and the average number of objects included in each CPM (column CPM Objects). The results are provided for different DCC configurations: considering only DCC Access, and considering DCC Access and DCC Facilities. In addition, the table differentiates the obtained results with the Reactive and Adaptive approaches at DCC Access.

Table 17 shows that the integration of the baseline generation rules with DCC Access (both Reactive and Adaptive approaches) does not change the number of CPMs generated and the number of objects per CPM when compared to the scenario without DCC (Table 14 and Table 15). This is the case because DCC Access adapts the CPM transmission rate, but not the generation rate. When redundancy mitigation is introduced (e.g., in

LARM, RMLA and *e*RMLA), the number of CPMs generated and the number of objects per CPM depend on the received CPMs. The received CPMs are altered by DCC Access since DCC Access can drop packets to adapt the CPMs transmitted per second and control the channel load. As a consequence, the number of CPMs generated and the number of objects per CPM tend to increase with DCC Access when it is integrated with LARM, RMLA and *e*RMLA (Table 17). When no packets are dropped by DCC Access, the proposed techniques generate (approximately) the same number of CPMs per second and include the same number of objects per CPM compared to the scenario without DCC. Packet drops are visible in Table 17 when the number of CPMs transmitted is lower than the number of CPMs generated. Packet drops are avoided when the channel load is low (DCC Access is not activated) or when the CPM generation frequency is lower than the limit provided by DCC Access. When considering DCC Access with the Reactive approach, all the techniques suffer from packet drops, except *e*RMLA. This is the case because only *e*RMLA avoids the generation of frequent and small CPMs. When DCC Access with the Adaptive approach is used, the number of CPMs transmitted is equal to the number of CPMs generated for all the techniques, except the baseline generation rules. In this case, the CBR for all the techniques was not sufficiently high to activate the Adaptive approach, and it was only activated for the baseline generation rules that generated a CBR of 82.1% when DCC was not applied (Table 16).

When both DCC Access and Facilities are used, the results reported in Table 17 show that DCC Facilities is able to effectively eliminate all packet drops. This is the case because the number of CPMs generated is equal to the number of CPMs transmitted for all the techniques independently of whether using the Reactive or Adaptive approaches for DCC Access. Instead of dropping CPMs, DCC Facilities modifies the *T_GenCpm* dynamically to adapt the CPMs generated to the amount of resources that can be transmitted by DCC Access. As a consequence, DCC Facilities also changes the number of objects included in each CPM. This is the case because when *T_GenCpm* is increased, more objects will satisfy the baseline generation rules since the last CPM transmitted. However, the proposed techniques under DCC Access Adaptive report a similar number of objects per CPM and CPM generation rate when compared to the scenario without DCC. This is the case because the CBR generated by the proposed techniques was not sufficient to activate DCC Access Adaptive.

Table 17. Average CBR, rate of CPMs generated and transmitted per second and number of objects per CPM in the high traffic density scenario when only CPMs are generated

DCC configuration	**Techniques**	**DCC Reactive**				**DCC Adaptive**			
		CBR	**CPM Gen**	**CPM Tx**	**CPM Objects**	**CBR**	**CPM Gen**	**CPM Tx**	**CPM Objects**
DCC Access	Baseline	40.5%	9.6Hz	5.8Hz	6.4	67.0%	9.6Hz	7.2Hz	6.4
	LARM	39.1%	7.1Hz	4.9Hz	9.6	46.3%	6.2Hz	6.2Hz	2.1
	RMLA	42.0%	6.6Hz	4.9Hz	10.6	43.3%	5.1Hz	5.1Hz	3.2
	*e*RMLA	42.3%	2.2Hz	2.2Hz	17.4	42.1%	2.1Hz	2.1Hz	17.4
DCC Access + Facilities	Baseline	39.1%	4.9Hz	4.9Hz	9.3	62.0%	4.9Hz	4.9Hz	9.3
	LARM	39.0%	4.7Hz	4.7Hz	3.6	46.4%	6.2Hz	6.2Hz	2.1
	RMLA	39.0%	4.1Hz	4.1Hz	5.0	43.0%	5.1Hz	5.1Hz	3.2
	*e*RMLA	37.7%	2.0Hz	2.0Hz	17.7	42.0%	2.1Hz	2.1Hz	17.4

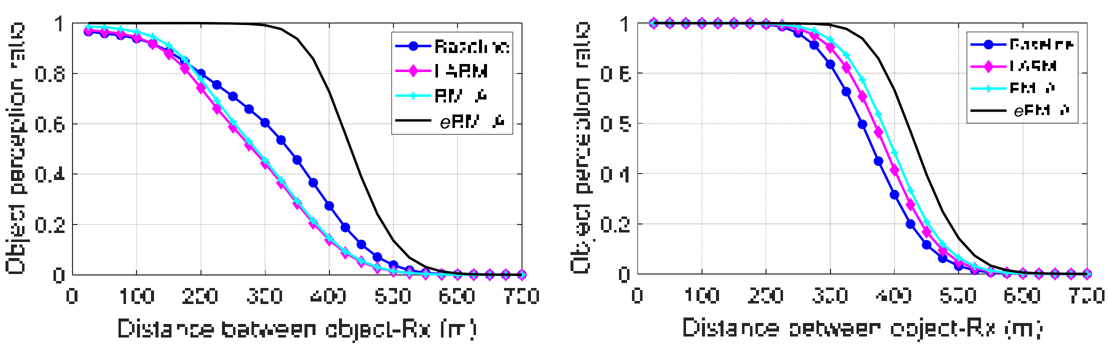
The impact of DCC on the object perception ratio is shown in Figure 48. Figure 48a and b show the results obtained with DCC Access only, while Figure 48c and d show the results when both DCC Access and Facilities are considered. As expected, the packets dropped by DCC Access with the Reactive approach significantly reduce the object perception ratio (Figure 48a). This degradation also results from the well-known synchronization problem [2] (explained in Section 5.3) observed with the Reactive approach of DCC Access in which vehicles synchronize with each other and transmit nearly at the same time increasing the probability of packet collisions. Only *e*RMLA is not affected by packet dropping because of its low CPM generation rate, that allows that CPMs do not wait in the DCC Access queue and are always transmitted. The Adaptive approach of DCC Access (Figure 48b) does not negatively impact any of the proposed techniques due to their low CBR.

Figure 48c shows that the object perception ratio achieved with the baseline generation rules when jointly considering DCC Access and DCC Facilities with the Reactive approach is degraded at larger distances when compared to the scenario considering only DCC Access (Figure 48a). This is mainly due to the following reasons. First, DCC Facilities does not mitigate the synchronization problem discussed previously when only one message type is considered. In this case, vehicles still tend to be synchronized and simultaneously transmit because the transmission times do not differ from the case with only DCC Access. Also, DCC Facilities adapts the *T_GenCpm* so that the CPMs generated can be transmitted by DCC Access with limited delay, which reduces the CPM transmission rate. The performance achieved with *e*RMLA is slightly reduced at larger distances compared to the scenario with only DCC Access because of a small reduction in the CPM transmission rate. Figure 48c also shows that the object perception ratio of

LARM and RMLA significantly increases compared to the scenario when only DCC Access is used (Figure 48a). This improvement is mainly produced because LARM and RMLA generate aperiodic CPMs with DCC Facilities (LARM and RMLA sometimes omit CPMs due to the use of redundancy mitigation and Look-Ahead). This reduces the probability that all vehicles simultaneously transmit and hence combats the synchronization problem.

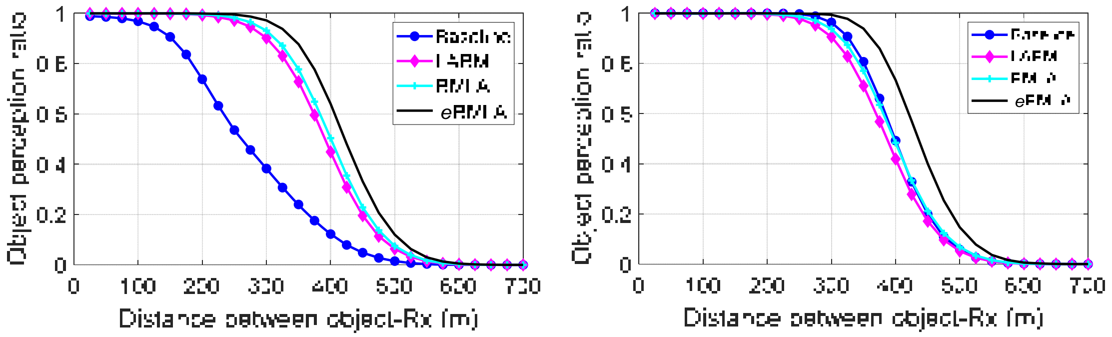
Figure 48d shows that the object perception ratio obtained with the proposed techniques when jointly considering DCC Access and DCC Facilities with the Adaptive approach is close to the one obtained when only DCC Access is used (Figure 48b). This is the case because the proposed techniques reduce the CBR below 50% (Table 17) and thus the Adaptive approach at DCC Access was not activated. However, the object perception ratio achieved with the baseline generation rules improves using the Adaptive approach at DCC Access and DCC Facilities. This is the case because DCC Facilities reduce the CPM transmission rate and increase the number of objects in each CPM. This eventually reduces the CBR and improves the percentage of CPMs successfully received.

The results depicted in Figure 48 clearly show that the highest object perception ratio is obtained with *e*RMLA independently of the DCC configuration. *e*RMLA is able to increase the distance at which an object perception ratio of 0.9 is achieved compared to the baseline generation rules by nearly 180% and 27% when using DCC Access only with the Reactive and Adaptive approaches respectively. The improvement is equal to 116% and 8% when using both DCC Access and Facilities, and DCC Access is configured with the Reactive and Adaptive approaches, respectively.



(a) DCC Access (Reactive)

(b) DCC Access (Adaptive)

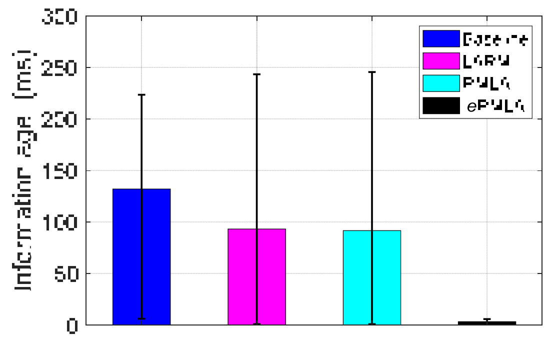


(c) DCC Access (Reactive) + Facilities (d) DCC Access (Adaptive) + Facilities

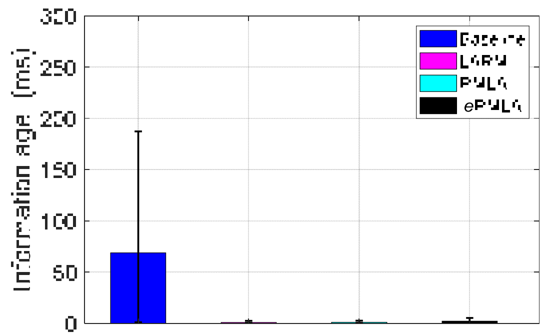
Figure 48. Object perception ratio as a function of the distance between the detected object and the vehicle receiving the CPM for different DCC configurations in the high traffic density scenario.

Figure 49 depicts the information age experienced with the baseline generation rules and the proposed techniques with all the DCC configurations evaluated. When only DCC Access is used, the information age generally increases (up to 250 ms) compared with the scenario without DCC (less than 5 ms) because of the waiting time of the packets at the DCC Access queues. The information age does not increase with *e*RMLA and DCC Access Reactive (Figure 49a) because the proposed technique reduces the channel load, and packets are not dropped or queued at the access layer. A similar trend occurs for all the proposed techniques when using DCC Access Adaptive (Figure 49b) since the channel load they generate is not sufficiently high to activate DCC Access. In this case, the proposed techniques obtain an information age below 5 ms, while the information age increases up to around 190 ms with the baseline generation rules.

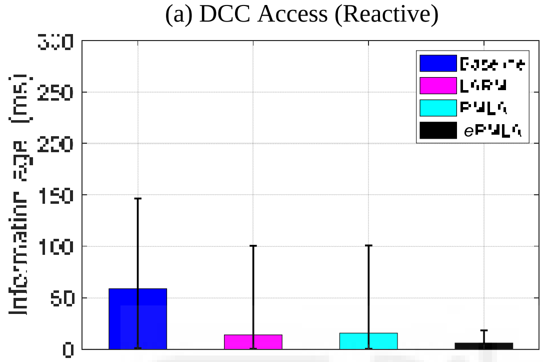
When DCC Access and Facilities are used, the information age generally decreases compared to when only DCC Access is used. This is the case because DCC Facilities adapts the *T_GenCpm* based on the upper limit of the fraction of time that the vehicle is allowed to transmit (provided by DCC Access) and CPMs tend to wait less time in the DCC Access queues. However, the information age is still significantly higher than when DCC is not used. When DCC Facilities is combined with DCC Access Reactive (Figure 49c), the information age for the baseline generation rules, LARM and RMLA are significantly reduced compared to when only DCC Access Reactive is applied. When DCC Facilities is combined with DCC Access Adaptive (Figure 49d), a significant reduction of the information age is also observed with the baseline generation rules. The proposed techniques achieve a significantly lower information age because the channel load they generate is not high enough for DCC Access to be activated. This eliminates packet drops and queuing at the access layer that ultimately reduces the information age to a negligible level.



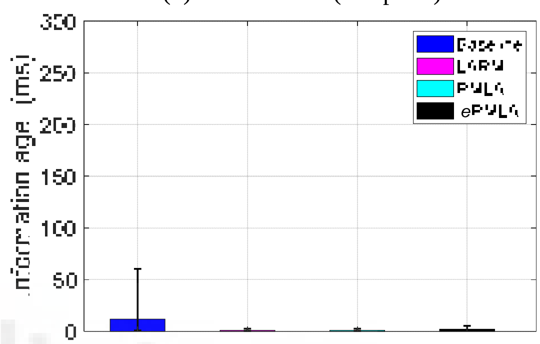
(a) DCC Access (Reactive)



(b) DCC Access (Adaptive)



(c) DCC Access (Reactive) + Facilities



(d) DCC Access (Adaptive) + Facilities

Figure 49. Average information age for CPMs with and without DCC in the high traffic density scenario. The bars represent the average values and the vertical lines represent the 5th and 95th percentiles.

8.4.2 CPMs and CAMs

This section complements previous evaluations with a scenario where all vehicles generate and transmit CAMs and CPMs on the same radio channel. The transmission of CAMs increases the channel load and activates DCC with higher probability. CAMs and CPMs are configured with the same DCC profile so that they share the channel equally. Table 18 shows the average CBR, the average rate of CAMs and CPMs generated and transmitted per second, and the average number of objects included in each CPM for the baseline generation rules and the proposed techniques under all DCC configurations. The transmission of CAMs and CPMs significantly increases the channel load compared with the previous section (Table 17). This results in packet drops for all techniques under evaluation when using only DCC Access. With DCC Access Reactive, approximately 50% of CAMs and CPMs are dropped, and no significant differences are observed among techniques since DCC Access Reactive adapts the message transmission rate without considering the message size. DCC Access Adaptive tolerates higher channel load levels and drops less packets (between 25% and 45% approximately). In addition, DCC Access

Adaptive does take into account the message size because it takes into account the time consumed by message transmissions. As a consequence, higher differences can be observed among the proposed techniques, being *e*RMLA the one with the lowest number of CPMs generated and transmitted per second due to their higher number of objects. When only DCC Access is used, Table 18 also shows that the highest number of CPMs dropped is obtained with the baseline generation rules, since it generates the smallest CPMs and thus has higher overhead. It also shows that the lowest number of CPMs dropped is obtained with *e*RMLA because it generates the CPMs with the higher number of objects.

When DCC Access and Facilities are used, *T_GenCam* and *T_GenCpm* are dynamically modified to adapt the number of CAMs and CPMs generated to the upper limit of the fraction of time that the vehicle is allowed to transmit. This significantly reduces the percentage of CAMs and CPMs that are dropped compared with the scenario with only DCC Access (Table 18). This reduction is particularly relevant when DCC Access Adaptive is combined with DCC Facilities that results in 11.5% CPM drops and 8.3% CAM drops with the baseline generation rules. The proposed techniques reduce the percentage of dropped messages. In fact, with *e*RMLA, no CAMs or CPMs are dropped when DCC Access and Facilities are utilized (independently of whether using DCC Access Adaptive or Reactive). As analyzed below, this could have a positive impact on cooperative perception since all the CPMs generated are effectively transmitted.

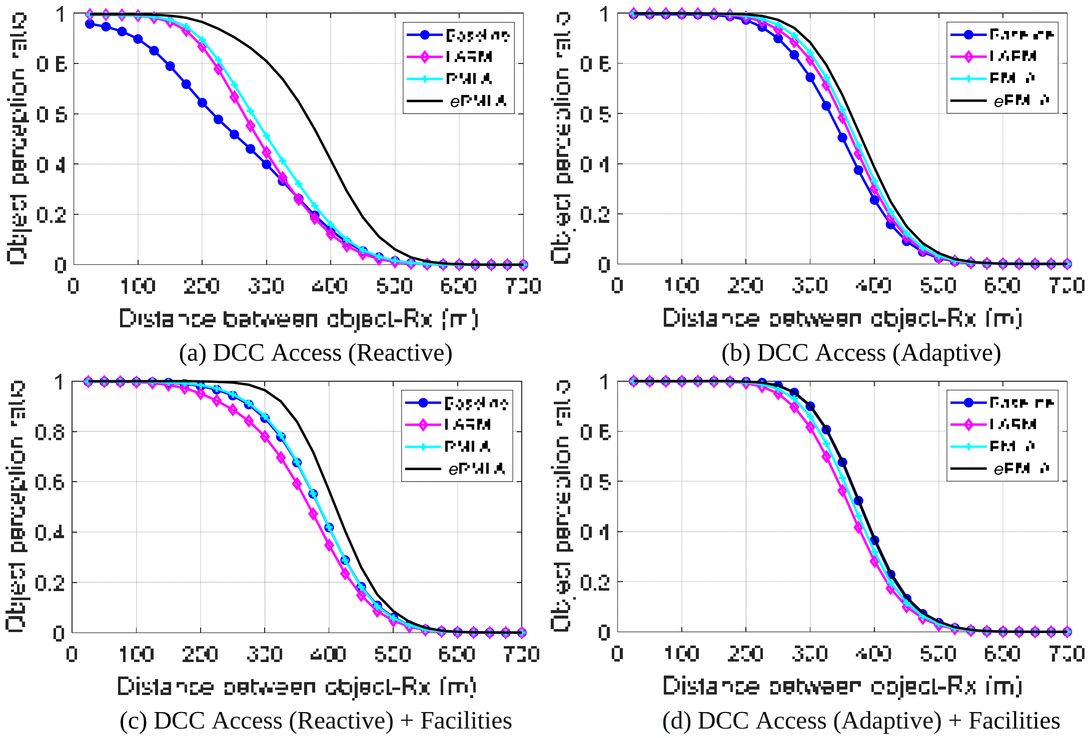
Table 18 also shows that the more efficient generation and transmission of CPMs affect the rate of CAMs that can be transmitted. As it can be observed, the rate of CAMs transmitted increases when the proposed techniques are used, for all the DCC configurations, and especially when *e*RMLA is used because its higher transmission efficiency. The higher CAM transmission rate would benefit other applications and services that would receive more frequent information about the transmitting vehicle.

Table 18. Average CBR, rate of CAMs and CPMs generated and transmitted per second and number of objects per CPM in the high traffic density scenario when CAMs and CPMs are generated

DCC configuration	**Techniques**	**DCC Reactive**						**DCC Adaptive**					
		CBR	**CAM Gen**	**CAM Tx**	**CPM Gen**	**CPM Tx**	**CPM Objects**	**CBR**	**CAM Gen**	**CAM Tx**	**CPM Gen**	**CPM Tx**	**CPM Objects**
DCC Access	Baseline	38.2%	3.3Hz	1.4Hz	9.6Hz	5.0Hz	6.4	68.2%	3.3Hz	1.8Hz	9.6Hz	6.2Hz	6.3
	LARM	48.5%	3.3Hz	1.5Hz	6.4Hz	3.4Hz	11.5	66.1%	3.3Hz	2.3Hz	7.3Hz	4.9Hz	7.3
	RMLA	50.1%	3.3Hz	1.5Hz	6.3Hz	3.4Hz	11.8	65.9%	3.3Hz	2.3Hz	6.5Hz	4.4Hz	8.6
	eRMLA	53.9%	3.3Hz	1.5Hz	6.1Hz	3.0Hz	12.2	65.6%	3.3Hz	2.5Hz	4.4Hz	2.8Hz	14.2
DCC Access + Facilities	Baseline	47.9%	1.1Hz	0.5Hz	6.2Hz	4.2Hz	8.1	62.5%	2.4Hz	2.2Hz	2.6Hz	2.3Hz	16.3
	LARM	41.2%	1.5Hz	1.3Hz	4.4Hz	3.5Hz	8.5	62.9%	2.4Hz	2.2Hz	4.6Hz	4.3Hz	5.6
	RMLA	46.7%	1.5Hz	1.3Hz	4.0Hz	3.2Hz	10.0	62.4%	2.3Hz	2.2Hz	3.9Hz	3.6Hz	8.2
	eRMLA	51.8%	1.3Hz	1.3Hz	2.3Hz	2.3Hz	17.4	59.4%	2.5Hz	2.5Hz	1.9Hz	1.9Hz	17.8

Figure 50 depicts the object perception ratio achieved with all DCC configurations when CAMs and CPMs are transmitted on the same channel. The figure shows that the highest perception is again obtained with *e*RMLA for all DCC configurations. However, the perception achieved decreases compared to the scenario without CAMs since CAMs consume part of the bandwidth and generate additional interferences. The degradation experienced by LARM and RMLA due to the transmission of CAMs is smaller when only DCC Access is used (Figure 50a and b). The baseline generation rules achieved the lowest perception ratio when only DCC Access is used (especially with DCC Access Reactive) due to the synchronization problem.

Combining DCC Facilities and DCC Access generally improves the object perception ratio compared with only using DCC Access for all the techniques considered (Figure 50c and d). A significant increase of the object perception ratio is observed especially for LARM and RMLA when DCC Facilities is used with DCC Access Reactive because the lower number of CPMs dropped. DCC Facilities helps alleviating the synchronization problem observed with DCC Access Reactive even when the baseline generation rules are considered (Figure 50a and Figure 50c). On the other hand, similar results are obtained with and without DCC Facilities when using DCC Access Adaptive (Figure 50b and Figure 50d). The main difference is that the use of DCC Facilities reduces significantly the CPM generation rate of the baseline generation rules, reduces the dropped CPMs and increases the CPM size. This improves the perception achieved with the baseline generation rules (Figure 50d).



(a) DCC Access (Reactive) (b) DCC Access (Adaptive)

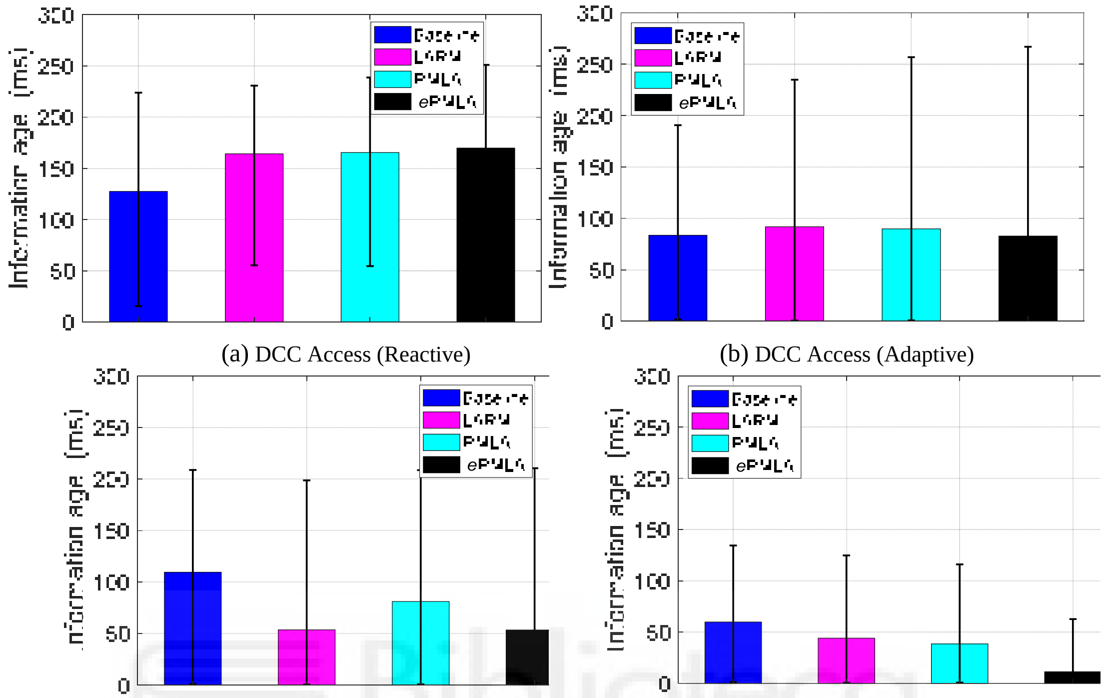
(c) DCC Access (Reactive) + Facilities (d) DCC Access (Adaptive) + Facilities

Figure 50. Object perception ratio as a function of the distance between the detected object and the vehicle receiving the CPM for different DCC configurations when CAMs and CPMs are transmitted on the same channel in the high traffic density scenario.

Figure 51 reports the information age obtained with the baseline generation rules and the proposed techniques with all DCC configurations when both CAMs and CPMs are transmitted on the same channel. When only DCC Access is used, the information age generally increases compared with the scenario without CAMs since DCC Access is now activated as the CAMs increase the channel load. The baseline generation rules slightly reduce the information age compared with the proposed techniques when only using DCC Access, but this is achieved at the expense of a lower object perception ratio (Figure 50). As expected, the DCC Access Reactive approach increases the information age for all the techniques evaluated compared with the DCC Access Adaptive approach.

When DCC Facilities is combined with DCC Access, the information age is in general reduced, especially when using the proposed techniques. With DCC Access Reactive and DCC Facilities (Figure 51c), LARM and *e*RMLA reduce the average information age compared to the baseline generation rules by around 50%. With DCC Access Adaptive and DCC Facilities (Figure 51d), *e*RMLA reduces the average information age by a factor of 5 compared to the baseline generation rules, and by a factor of 4 compared to LARM and RMLA, approximately. This is the case because *e*RMLA generates CPMs at a lower frequency, and most of the time the DCC Access gate is open when a CPM is generated.

This result demonstrates that *e*RMLA can facilitate the transmission of CPMs with a low latency even under the presence of CAMs.



(a) DCC Access (Reactive)

(b) DCC Access (Adaptive)

(c) DCC Access (Reactive) + Facilities

(d) DCC Access (Adaptive) + Facilities

Figure 51. Average information age for CPMs with and without DCC when CAMs and CPMs are transmitted on the same channel in the high traffic density scenario. The bars represent the average values and the vertical lines represent the 5th and 95th percentiles

8.5 Summary and additional results

This chapter has proposed and evaluated three methods to combine the proposed techniques in order to improve the effectiveness of cooperative perception while ensuring their scalability. The proposed methods combine, for the first time, the baseline generation rules for cooperative perception messages with mechanisms to control the redundancy and to efficiently organize the information about detected objects in order to avoid the frequent transmission of small messages that increase the communications overhead. The study has evaluated the effectiveness and scalability of the proposed techniques under different traffic density scenarios and considering the integration with congestion control mechanisms and the coexistence of cooperative perception messages and awareness messages. The conducted evaluation has demonstrated that the proposed combinations improve the perception of CAVs and reduce the information age compared to the baseline generation rules. In addition, the combinations reduce the channel load and improve the scalability of cooperative perception services. The conducted evaluation has demonstrated that the most effective way to combine the baseline generation rules with redundancy control and Look-Ahead mechanisms is by first applying the baseline generation rules, then redundancy control and finally the look-ahead mechanism to all detected objects, including those initially removed by the redundancy control scheme. This combination, referred to as *e*RMLA in this study, achieves the highest perception and lowest information age and channel load thanks to a better balance between object redundancy and communications overhead.

The submitted paper [66] extends the results presented in this chapter by analyzing the operation and performance also in an additional highway traffic density (180 veh/km). The paper also considers an additional metric defined as the percentage of detected objects that are included in each CPM. This metric helps to analyze the effectiveness of the techniques by verifying whether the techniques include all detected objects in each generated CPM. This is relevant because transmitting all the detected objects in the same CPM helps receiving vehicles to rapidly identify the objects that are detected by other nearby vehicles. Also, the paper reports PDR results computed under different traffic densities to further justify the results of the achieved CBR and the object perception ratio. The additional analysis reported in the submitted paper derives the same conclusions as those presented in this chapter.

9 Conclusions and future work

Cooperative perception enables connected and automated vehicles to share information about detected objects to improve the sensing accuracy, confidence, and perception of the driving environment. This thesis has studied the performance of cooperative perception, and identified challenges and inefficiencies of existing solutions. The thesis has then proposed different techniques to improve the overall efficiency and scalability of cooperative perception and the underlying vehicular network. The study performed in this thesis considers the current status of the ETSI standardization work on cooperative perception that includes the definition of the CPM format and the generation rules to maximize the scientific and industrial impact of the conducted research and proposed solutions. The work carried out within the framework of this thesis can be considered one of the first studies on cooperative perception and most of the conducted evaluations and the proposed techniques presented in this thesis are incorporated and published in the ETSI Technical Report and Technical Specification for collective perception.

9.1 Dimensioning analysis

The research undertaken in this thesis started with an extensive review of the state-of-the-art in cooperative perception including related standards. The review conducted showed that existing studies mainly focus on the overall performance of cooperative perception but do not analyze the message generation and DCC configurations in detail. Then a detailed dimensioning study was identified as essential to study the importance and criticality of some components, parameters and configurations that can have an impact on the performance and effectiveness of cooperative perception.

To conduct the dimensioning study, a simulation platform was implemented to evaluate cooperative perception. At the time of initiating the thesis, there were no open source platforms for the evaluation of cooperative perception solutions. This platform has been implemented in this thesis using ns3 and implementing an accurate modeling of the cooperative perception service, the radio access technology, the different layers of the V2X communications protocol stack (including DCC), an accurate radio propagation model, the sensing capabilities of the vehicles and realistic road traffic models.

Using the simulation platform, a dimensioning study on cooperative perception has been conducted. The study includes the evaluation of the generation rules defined by ETSI (baseline generation rules) and compares it with periodic generation policies to analyze its effectiveness and to identify existing potential inefficiencies. The analysis results show that the baseline generation rules achieve an interesting balance between perception capabilities and communications performance when compared with periodic ones. However, the baseline generation rules present certain inefficiencies that can overload the communications channel and limit the scalability of the cooperative perception service. The first inefficiency is related to the transmission of redundant information since multiple CAVs can detect the same object simultaneously and include its information on their CPMs. The second inefficiency is related to the generation of a high number of CPMs with a small payload.

The dimensioning study also includes a detailed analysis on several configurations and components of cooperative perception. The study demonstrates that cooperative perception can complement on-board sensors and increase the vehicle's sensor perception beyond its sensors' field of view. In particular, the study shows that very high perception levels can be achieved from low penetration rates (from 40%) and the sensors' characteristics do not greatly impact on the cooperative perception with a high market penetration rate. The results also show that the perception achieved with cooperative perception strongly depends on the sensors' field of view and range when the market penetration rate is low. The study then shows that the perception achieved with cooperative perception degrades with high density and when sensor fusion is not implemented because these factors increase the channel load in the network and impact on the V2X communications performance.

Finally, the dimensioning study analyzed the impact of DCC on cooperative perception since DCC can alter the generation and transmission of CPMs and hence impact the effectiveness of cooperative perception. The study demonstrates that using congestion control protocols only at the Access layer augments the latency (or information age) of CPMs. This reduces the value of cooperative perception and can negatively impact connected automated driving that requires low latency for safe driving. This study then demonstrates for the first time that this challenge can be addressed through the combination of DCC Access and DCC Facilities. This combination increases the perception and reduces the latency through the dynamic adaptation of the rate at which cooperative messages are generated and transmitted, and thus ultimately benefits the V2X network and the effectiveness of cooperative perception.

9.2 Redundancy Mitigation

One of the main challenges identified in the dimensioning study is that the baseline generation rules generate significant detected object redundancy that can compromise the network scalability. The thesis illustrates and quantifies the redundancy problem in cooperative perception in detail considering the baseline generation rules. It then proposes a redundancy mitigation technique to address the identified inefficiency. The proposal extends the baseline generation rules to filter out the detected objects from the CPM that have not significantly changed their position, speed, and heading since the last time they were received as part of a CPM. The results obtained in this thesis show that the proposed redundancy mitigation technique significantly reduces the redundancy and channel load and improves the reliability of V2X communications. Also, the redundancy mitigation technique maintains the same perception performance (with significantly fewer messages) than the current baseline generation rules for safety-critical short and medium distances. It is also able to improve the perception at larger distances when the traffic density is high. These benefits are obtained while still providing object updates below the threshold (i.e., 4 m) defined by the baseline generation rules.

9.3 Look-Ahead

Another cooperative perception challenge identified in this thesis is related to the generation of frequent CPMs that contain small number of objects. This increases the communications overhead and degrades the V2X communications reliability as well as the perception capabilities due to the high overhead. To address these problems, the thesis proposes and explains the Look-Ahead technique that extends the baseline generation rules to reorganize the transmission of objects. The Look-Ahead technique is triggered every time a new CPM must be generated by the baseline generation rules. Then, the proposed technique looks ahead and predicts if any of the detected objects that are not included in the current CPM would be included in the following CPM. If this is the case, the transmission of these objects is anticipated and included in the current CPM by Look-Ahead. This reorganization results in vehicles transmitting fewer messages, and each message includes information about a higher number of detected objects. The detailed analysis carried out on the performance achieved with the Look-Ahead and the baseline generation rules shows that Look-Ahead is able to simultaneously reduce the overhead and the channel load, and improve the reliability of V2X communications and the perception of CAVs. This is achieved by reorganizing the transmission and content of CPMs while still providing object updates more frequently than the threshold (i.e., 4 m) defined by the baseline generation rules.

9.4 Combination of Look-Ahead and Redundancy Mitigation

Look-Ahead and the redundancy mitigation proposal have been designed independently of each other, and they can have opposite effects on the generation of CPMs. In this context, the thesis finally investigates how Look-Ahead and redundancy mitigation should be combined to further improve cooperative perception and the system's scalability. To this aim, the thesis proposed three different methods to combine the baseline generation rules for CPMs with mechanisms to control the redundancy and to efficiently organize the information about detected objects in order to avoid the frequent transmission of small messages that increase the communications overhead. The study has evaluated the effectiveness and scalability of the proposed techniques under different traffic density scenarios and considering the integration with congestion control mechanisms and the coexistence of CPMs and awareness messages. The conducted evaluation has demonstrated that the proposed techniques improve the perception of CAVs and reduce the information age compared to the baseline collective perception service. In addition, the techniques reduce the channel load and improve the scalability of cooperative perception services. The conducted evaluation has also demonstrated that the most effective way to combine techniques is by first applying the generation rules, then redundancy control and finally the Look-ahead mechanism to all detected objects, including those initially removed by the redundancy control scheme. This combination technique is referred to as *e*RMLA, and this technique (*e*RMLA) better balances object redundancy and communications overhead and achieve the highest perception and lowest information age and channel load.

9.5 Future research directions

This thesis has demonstrated the potential benefits of cooperative perception for the development of connected and automated driving, and provided solutions to improve the efficiency and scalability. The contributions proposed in this thesis have significantly contributed to the ETSI standardization process and some of the main future lines of research identified are detailed below.

The standardization bodies initially developed basic safety and traffic efficiency applications for CAVs to be transmitted using a single radio interface operating on a single channel. However, the increased bandwidth needs of CAVs and the development of the new V2X messages (e.g., VRU Awareness Messages and Maneuver Coordination Messages) will increase the channel load significantly and could negatively impact the V2X communications performance. To address this challenge, the adoption of multi-channel operation (MCO) could support the growing demand of communications bandwidth by utilizing multiple radio communications channels in parallel. However, the impact of MCO on the cooperative perception has to be analyzed in detail, and the MCO specifications (recently published) leave the door open for the community to design MCO solutions that dynamically identify the channel to be used for each message taking into account the application requirements and the capabilities of the lower layers.

The cooperative perception for CAVs can be deployed using different access technologies such as IEEE 802.11p/ITS-G5 or IEEE 802.11bd, LTE-V2X or 5G NR V2X. In this thesis, the work done on cooperative perception is technology agnostic and is evaluated using the IEEE 802.11p/ITS-G5 access technology. Few studies have analyzed cooperative perception in other access technologies. To the author’s knowledge, no study compares and analyzes the impact of the access technology (IEEE 802.11p/ITS-G5 or IEEE 802.11bd, LTE-V2X and 5G NR V2X) on cooperative perception. This comparison study will provide additional insights on how the access technologies impact on the performance and operations of the cooperative perception. Since the thesis analyzes the impact of congestion control on cooperative perception using the ITS-G5 access technology, it could then be interesting to analyze the impact of congestion control on cooperative perception using the LTE-V2X or 5G NR access technology, that embed their own congestion control mechanism. This mechanism is open and could include adapting the modulation and coding scheme, controlling the number of sub-channels and re-transmissions, and reducing the transmission power to control the load.

The impact of DCC on cooperative perception has been analyzed in this thesis because DCC Access and DCC Facilities could control the generation and transmission of CPMs. It could be then interesting to design a feed-back based solutions where DCC informs cooperative perception about the packet control. This feedback system from DCC could help cooperative perception to handle the generation and contents of the CPMs more efficiently. For example, when the DCC drops a CPM at the access layer, this information can be feedback to the cooperative perception so that the cooperative perception immediately considers the dropped objects in the next generation of CPM, which could increase the freshness of the reported objects. Alternatively, based on the CBR feedback from DCC, the redundancy mitigation in cooperative perception could adjust the redundancy threshold to control the number of redundant objects included in the CPM, which could increase the probability of successful delivery of the critical (non-redundant) objects.

The redundancy mitigation technique proposed and analyzed in this thesis can be considered as a natural extension of the baseline generation rules since it is also based on the mobility or dynamics of the objects. However, other redundancy mitigation techniques are also reported in the ETSI Technical Report and Technical Specification, which could be interesting to analyze and compare with the redundancy mitigation technique proposed in this thesis. Also, it could be interesting to analyze the combination of Look-Ahead with more than one redundancy mitigation technique since it filters the redundant objects using different techniques.

So far in this thesis, the cooperative perception is evaluated with only the participation of CAVs. However, analyzing the cooperative perception with RSUs could also be interesting because RSUs could increase the communications reliability due to their higher antenna height. It could be then interesting to analyze the scenarios (e.g., intersections) where RSUs role is important in enhancing the effectiveness of the cooperative perception.

In recent years, Multi-access Edge Computing (MEC) with 5G networks has been adopted in many automotive industries for V2X communications. The 5G Uu interface allows vehicles to transmit V2X messages to the Multi-access Edge Computing (MEC) data centers and vice versa using the cellular network. The advantage of using 5G Uu interface is to provide the network bandwidth between the MEC and vehicles that helps achieve low latency requirements and high throughput. However, a large amount of data is generated with the growing high traffic density which demands a more robust messaging protocol. This messaging protocol will effectively manage the contents and messages that needs to be transmitted and processed in the MEC data centers while guaranteeing the demanding low-latency limit and throughput. However, the messaging protocol could impact on the operation and performance of the cooperative perception and thus need to be analyzed in detail.

The thesis shows the effectiveness of the cooperative perception proposed solutions in the simulation environment. Analyzing the cooperative perception solutions in real prototype implementation would then complement the existing analysis and deliver a valuable contribution to the research field. However, the real hardware implementation considerably increases the required resources and cost. To lower it, the evaluations could consider opting for an empirical model for CPMs generated from the dataset traces collected from the CAVs driven on real roads. Another option could be analyzing the cooperative perception in the emulation environment where few real hosts (real CAVs) can participate and exchange messages with other large numbers of nodes in the simulation.

10 Conclusiones y trabajo futuro

La percepción cooperativa permite que los vehículos autónomos conectados compartan información sobre los objetos que detectan para mejorar la precisión con la que detectan su entorno de conducción. Esta tesis ha estudiado el rendimiento de la percepción cooperativa e identificado las principales ineficiencias de las soluciones existentes. A partir de dicha identificación, la tesis ha propuesto diferentes técnicas para mejorar la eficiencia y escalabilidad de la percepción cooperativa y, por tanto, la red de comunicaciones vehicular. El estudio realizado en esta tesis considera el estándar actual sobre percepción cooperativa de ETSI que incluye la definición del formato del mensaje CPM y las reglas de generación para maximizar el impacto científico e industrial de las investigaciones realizadas y las soluciones propuestas. El trabajo realizado en el marco de esta tesis puede considerarse uno de los primeros estudios sobre percepción cooperativa y la mayoría de las evaluaciones realizadas y las técnicas propuestas presentadas en esta tesis están incorporadas y publicadas en el informe técnico y la especificación de ETSI sobre percepción cooperativa.

10.1 Estudio de dimensionado

La investigación realizada en esta tesis comenzó con una revisión exhaustiva del estado del arte sobre percepción cooperativa, incluidos los estándares relacionados. La revisión realizada mostró que los estudios existentes se centran principalmente en el rendimiento general de la percepción cooperativa, pero no analizan en detalle la generación de mensajes, ni el control de congestión o DCC. Esta revisión identificó la necesidad de realizar un estudio de dimensionamiento detallado para analizar la importancia y criticidad de algunos componentes, parámetros y configuraciones que pueden tener impacto en el rendimiento y efectividad de la percepción cooperativa.

Para realizar el estudio de dimensionamiento se implementó una plataforma de simulación para, puesto que en el inicio de la tesis no existían plataformas de código abierto que permitieran la evaluación de soluciones de percepción cooperativa. Esta plataforma ha sido implementada en esta tesis usando el simulador de código abierto ns3 e implementando un modelado detallado del servicio de percepción cooperativa, la tecnología de acceso de radio, las diferentes capas de la pila de protocolos de comunicaciones V2X (incluyendo DCC), un modelo de propagación radio preciso, las capacidades de detección de los vehículos (sensores) y modelos realistas de tráfico por carretera.

Utilizando la plataforma de simulación se ha realizado un estudio de dimensionamiento de la percepción cooperativa. El estudio incluye la evaluación de las reglas de generación definidas por ETSI (denominadas reglas baseline en esta tesis) y las compara con políticas de generación de mensajes periódicos para analizar su eficacia e identificar las posibles ineficiencias existentes. Los resultados del análisis muestran que las reglas baseline logran un equilibrio interesante entre las capacidades de percepción y el rendimiento de las comunicaciones en comparación con las periódicas. Sin embargo, las reglas de generación baseline presentan ciertas ineficiencias que pueden sobrecargar el canal de comunicaciones y limitar la escalabilidad del servicio de percepción cooperativa. La primera ineficiencia está relacionada con la transmisión de información redundante ya que múltiples CAV pueden detectar el mismo objeto simultáneamente e incluir su información en sus CPMs. La segunda ineficiencia está relacionada con la generación de una gran cantidad de CPMs con un reducido tamaño.

El estudio de dimensionamiento también incluye un análisis detallado sobre varias configuraciones y componentes de la percepción cooperativa. El estudio demuestra que la percepción cooperativa puede complementar los sensores embarcados en el vehículo y aumentar la percepción del vehículo más allá del campo de visión de sus sensores. En particular, el estudio muestra que se pueden lograr niveles de percepción muy elevados a partir de tasas de penetración bajas (a partir del 40%) y que las características de los sensores no tienen un gran impacto en la percepción cooperativa con una tasa de penetración de mercado alta. Los resultados también muestran que la percepción lograda con la percepción cooperativa depende en gran medida del campo de visión y el rango de detección de los sensores cuando la tasa de penetración en el mercado es baja. Además, el estudio muestra que la percepción lograda con la percepción cooperativa se degrada cuando la densidad aumenta y cuando no se implementa la fusión de sensores porque estos factores aumentan la carga del canal radio e impactan en el rendimiento de las comunicaciones V2X.

Finalmente, el estudio de dimensionamiento analizó el impacto de DCC en la percepción cooperativa ya que DCC puede alterar la generación y transmisión de CPMs. El estudio demuestra que el uso de protocolos de control de congestión solo en la capa de acceso aumenta la latencia de los CPMs. Esto reduce el valor de la percepción cooperativa y puede tener un impacto negativo en la conducción autónoma conectada que requiere baja latencia para una conducción segura. Además, este estudio demuestra por primera vez que este problema se puede abordar a través de la combinación de DCC Access y DCC Facilities. Esta combinación mejora la percepción y reduce la latencia a través de la adaptación dinámica de la velocidad a la que se generan y transmiten los mensajes V2X y, por lo tanto, beneficia en última instancia a la red V2X y la eficacia de la percepción cooperativa.

10.2 Mitigación de redundancia

Uno de los principales problemas identificados en el estudio de dimensionado es que las reglas de generación *baseline* generan una redundancia significativa de objetos detectados que puede comprometer la escalabilidad de la red. La tesis ilustra y cuantifica en detalle el problema de redundancia en la percepción cooperativa considerando las reglas de generación *baseline*. A continuación, propone una técnica de mitigación de redundancia para abordar la ineficiencia identificada. La propuesta amplía las reglas de generación *baseline* para filtrar los objetos detectados del CPM que no han cambiado significativamente su posición, velocidad y dirección desde la última vez que se recibieron como parte de un CPM. Los resultados obtenidos en esta tesis muestran que la técnica de mitigación de redundancia propuesta reduce significativamente la redundancia y la carga del canal y mejora la fiabilidad de las comunicaciones V2X. Además, la técnica de mitigación de redundancia mantiene el mismo rendimiento de percepción (con significativamente menos mensajes) que las reglas de generación *baseline* para distancias cortas y medias. También es capaz de mejorar la percepción a altas distancias cuando la densidad de tráfico es alta. Estos beneficios se obtienen sin dejar de proporcionar actualizaciones sobre objetos detectados por debajo del umbral (es decir, 4 m) definido por las reglas de generación *baseline*.

10.3 Look-Ahead

Otro problema de la percepción cooperativa identificado en esta tesis está relacionado con la frecuente generación de CPMs que contienen una pequeña cantidad de objetos. Esto aumenta la carga del canal radio y degrada la fiabilidad de las comunicaciones V2X así como las capacidades de percepción. Para abordar este problema, la tesis propone la técnica Look-Ahead que extiende las reglas de generación *baseline* para reorganizar la transmisión de objetos. La técnica Look-Ahead se activa cada vez que las reglas de generación *baseline* deben generar un nuevo CPM. Entonces, la técnica propuesta predice si alguno de los objetos detectados que no está incluido en el CPM actual se incluiría en el CPM siguiente. Si este es el caso, la transmisión de estos objetos se anticipa y se incluyen en el CPM actual por Look-Ahead. Esta reorganización da como resultado que los vehículos transmitan menos mensajes, y cada mensaje incluye información sobre una mayor cantidad de objetos detectados. El análisis detallado realizado sobre el rendimiento alcanzado con Look-Ahead y las reglas de generación *baseline* muestra que Look-Ahead es capaz de reducir simultáneamente la carga del canal, y mejorar la fiabilidad de las comunicaciones V2X y la percepción. Esto se logra mediante la reorganización de la transmisión y el contenido de los CPM sin dejar de proporcionar actualizaciones de objetos con más frecuencia que el umbral (es decir, 4 m) definido por las reglas de generación *baseline*.

10.4 Combinación de Look-Ahead y Mitigación de Redundancia

Look-Ahead y la propuesta de mitigación de redundancia se han diseñado de forma independiente y pueden tener efectos opuestos en la generación de CPM. En este contexto, la tesis finalmente investiga cómo Look-Ahead y la mitigación de redundancia deben combinarse para mejorar aún más la percepción cooperativa y la escalabilidad del sistema. Con este fin, la tesis propuso tres métodos diferentes para combinar las reglas de generación *baseline* para CPMs con mecanismos para controlar la redundancia y organizar eficientemente la información sobre los objetos detectados para evitar la transmisión frecuente de pequeños mensajes que aumentan la carga del canal. El estudio ha evaluado la eficacia y escalabilidad de las técnicas propuestas bajo diferentes escenarios de densidad de tráfico, considerando la integración con mecanismos de control de congestión y la coexistencia de CPMs con otros mensajes como CAMs. La evaluación realizada ha demostrado que las técnicas propuestas mejoran la percepción y reducen la latencia en comparación con las reglas de generación *baseline*. Además, las técnicas reducen la carga del canal radio y mejoran la escalabilidad del servicio de percepción cooperativa. La evaluación realizada también ha demostrado que la forma más efectiva de combinar técnicas es aplicando primero las reglas de generación *baseline*, luego el control de redundancia y finalmente el mecanismo Look-Ahead a todos los objetos detectados, incluidos aquellos inicialmente eliminados por el esquema de control de redundancia. Esta técnica de combinación se conoce como *e*RMLA, y es la que mejor equilibra la redundancia de objetos y la carga de comunicaciones, logrando los mejores niveles de percepción, latencia y carga.

10.5 Líneas de Investigación Futuras

Esta tesis ha demostrado los beneficios potenciales de la percepción cooperativa para el desarrollo de la conducción autónoma conectada, y ha proporcionado soluciones para mejorar su eficiencia y escalabilidad. Las contribuciones propuestas en esta tesis han contribuido notablemente al proceso de estandarización de ETSI y a continuación se detallan algunas de las principales líneas de investigación futuras identificadas.

Los organismos de estandarización como ETSI se han centrado hasta la fecha en el desarrollo de estándares para los servicios y aplicaciones básicos que emplean una sola interfaz en un solo canal radio. Sin embargo, las crecientes necesidades de ancho de banda de los CAV y el desarrollo de nuevos mensajes V2X (por ejemplo, mensajes para VRUs y mensajes de coordinación de maniobras) aumentarán significativamente la carga del canal y podrían afectar negativamente el rendimiento de las comunicaciones V2X. Para hacer frente a este desafío y dar soporte a la creciente demanda de ancho de banda, los estándares de ETSI para servicios y aplicaciones avanzados harán uso de MCO empleando múltiples canales radio en paralelo. Sin embargo, el impacto de MCO en la percepción cooperativa debe analizarse en detalle, y las especificaciones de ETSI sobre MCO (recién publicadas) dejan la puerta abierta para que la comunidad diseñe soluciones MCO que identifiquen dinámicamente el canal a utilizar para cada mensaje teniendo en cuenta los requisitos de la aplicación y las capacidades de las capas inferiores.

La percepción cooperativa para CAVs puede implementarse utilizando diferentes tecnologías de acceso, como IEEE 802.11p/ITS-G5 o IEEE 802.11bd, LTE-V2X o 5G NR V2X. En esta tesis, el trabajo realizado sobre percepción cooperativa es independiente de la tecnología y se evalúa utilizando la tecnología de acceso IEEE 802.11p/ITS-G5. Son escasos los estudios que han analizado la percepción cooperativa empleando otras tecnologías de acceso. Hasta la fecha, ningún estudio compara y analiza el impacto de la tecnología de acceso (IEEE 802.11p/ITS-G5 o IEEE 802.11bd, LTE-V2X y 5G NR V2X) sobre la percepción cooperativa. Este estudio de comparación proporcionaría información adicional sobre cómo las tecnologías de acceso impactan en el rendimiento y el funcionamiento de la percepción cooperativa. Dado que la tesis analiza el impacto del control de congestión en la percepción cooperativa utilizando la tecnología de acceso ITS-G5, sería interesante también analizar el impacto del control de congestión en la percepción cooperativa utilizando la tecnología de acceso LTE-V2X o 5G NR V2X, que integran sus propios mecanismo de control de congestión. El control de congestión en LTE-V2X y 5G NR V2X debe cumplir ciertos requisitos fijados por los estándares, pero se deja libertad al fabricante para el detalle de su implementación, pudiendo, por ejemplo, adaptar la modulación y codificación de cada paquete, controlar el número de subcanales y retransmisiones, o reducir la potencia de transmisión para controlar la carga.

El impacto de DCC en la percepción cooperativa se ha analizado en esta tesis ya que DCC Access y DCC Facilities podrían controlar la generación y transmisión de CPM. Este análisis revela que sería interesante diseñar soluciones basadas en retroalimentación donde DCC informe al servicio de percepción cooperativa sobre el control de los paquetes. Este sistema de retroalimentación de DCC podría ayudar a la percepción cooperativa a gestionar mejor la generación y el contenido de los CPMs de manera más eficiente. Por ejemplo, cuando el DCC Access descarte un CPM en la capa de acceso, podría retroalimentar esta información al servicio de percepción cooperativa para que tenga en cuenta que los objetos que se incluían en dicho CPM no han sido enviados, y por tanto los deberá incluir en el siguiente CPM. Alternativamente, si se retroalimenta la información sobre el CBR de DCC, la mitigación de redundancia de la percepción cooperativa podría ajustar el umbral de redundancia para controlar la cantidad de objetos redundantes incluidos en el CPM. Esto podría aumentar la probabilidad recepción de los objetos críticos (no redundantes).

La técnica de mitigación de redundancia propuesta y analizada en esta tesis puede considerarse como una extensión natural de las reglas de generación *baseline* ya que también se basa en la movilidad o dinámica de los objetos. Sin embargo, se han identificado otras técnicas de mitigación de redundancia en el informe técnico de ETSI sobre percepción cooperativa, que podrían ser interesantes de analizar y comparar con la técnica de mitigación de redundancia propuesta en esta tesis. Además, podría ser interesante analizar la combinación de Look-Ahead con más de una técnica de mitigación de redundancia ya que filtra los objetos redundantes utilizando diferentes técnicas.

Hasta el momento en esta tesis se evalúa la percepción cooperativa con sólo la participación de los CAV. Sin embargo, analizar la percepción cooperativa considerado nodos RSU también podría ser interesante porque los nodos RSU podrían aumentar la fiabilidad de las comunicaciones debido a su mayor altura de antena, y además podrían tener mejores sensores y campo de visión. Podría ser interesante analizar aquellos escenarios (por ejemplo, intersecciones) donde el papel de los nodos RSU es importante para mejorar la efectividad de la percepción cooperativa.

En los últimos años, se ha propuesto y estudiado el empleo de nodos MEC en el borde (*edge*) de la red celular 5G para dar soporte a las comunicaciones V2X. La interfaz 5G Uu permite que los vehículos transmitan mensajes V2X a los nodos MEC y viceversa utilizando la red celular. La ventaja de usar la interfaz 5G Uu reside en que la gestión del enlace se realiza de forma centralizada, y no distribuida, de forma que en teoría puede conseguir cumplir los requisitos de baja latencia y alto rendimiento. Sin embargo, también puede generar una gran cantidad de datos para que la red tenga un conocimiento detallado de las necesidades de comunicación de cada vehículo y pueda realizar esa gestión centralizada de forma óptima. Se requerirá, por tanto, un control de la información que los vehículos intercambian con la red y con el MEC, para que puedan garantizarse los límites de latencia y fiabilidad. El control de dicha información podrá afectar sin duda a la percepción cooperativa, por lo que deberá analizarse en detalle.

La tesis muestra la efectividad de las soluciones de percepción cooperativa propuestas en un entorno de simulación. El análisis de dichas soluciones sobre prototipos reales complementaría el estudio realizado con una importante contribución al campo de investigación. Sin embargo, la implementación en hardware real aumenta considerablemente los recursos necesarios y el coste. Para reducirlo, las evaluaciones podrían optar por un modelo empírico para los CPM generados a partir de datos recopilados sobre vehículos en carreteras reales. Otra opción podría ser la de analizar la percepción cooperativa en un entorno de emulación mixto en el que algunos vehículos reales pueden interactuar e intercambiar mensajes con un gran número de nodos en la simulación.

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Annex A.1 Publication

Analysis of Message Generation Rules for Collective Perception in Connected and Automated Driving

Gokulnath Thandavarayan, Miguel Sepulcre, Javier Gozalvez

***Abstract*— Collective Perception (CP) or cooperative sensing enables vehicles and infrastructure nodes to exchange sensor information to improve their perception of the driving environment. CP enables vehicles to detect objects (e.g. non-connected vehicles, pedestrians, obstacles, etc.) beyond their local sensing capabilities. ETSI is currently developing the European standards for collective perception or cooperative sensing. This includes defining which information should be exchanged about the detected objects, and how often it should be exchanged. To this aim, different CP generation rules for collective perception are currently under analysis, and this paper presents an in-depth analysis of their performance and efficiency. The conducted analysis highlights the existing trade-offs between performance (capacity to detect surrounding objects) and efficiency (redundant detection and transmission of the same detected objects). It also demonstrates the need to design advanced policies that dynamically control the redundancy on the wireless channel while ensuring the capacity to reliably detect the driving environment.**

Keywords*— Collective perception, cooperative sensing, message generation, connected and automated vehicles, CAV, V2X, vehicular networks, C-ITS, cooperative ITS.

I. INTRODUCTION

Automated Vehicles (AVs) are equipped with multiple exteroceptive sensors (e.g. lidars, radars, sonars and cameras) to perceive their local environment. The perception capabilities of each sensor are limited to a certain detection range and a given field of view. In addition, these capabilities can be impaired due to the presence of obstacles (obstructions) in the field of view, and adverse weather conditions, among others. These limitations can significantly degrade the perception capabilities of AVs, and hence negatively influence their safety and driving efficiency.

Connected and Automated Vehicles (CAVs) can improve their perception capabilities thanks to the exchange of sensor information using wireless technologies such as IEEE 802.11p/ITS-G5 [1] or C-V2X/LTE-V [2]. This is generally referred to as collective perception or cooperative sensing. Collective perception enables CAVs to improve their perception of the surrounding environment by receiving from other vehicles information about objects that are beyond their sensing range. It can also improve CAVs' detection accuracy and increase the confidence about the detected objects. Collective perception can also help mitigate the negative impact of adverse weather conditions on the sensing capabilities as well as the initial limited CAV market penetration rate. The collective perception concept can also be extended to infrastructure nodes with ITS sensing capabilities. These nodes can transmit and receive sensor information to/from vehicles to improve their respective knowledge of the driving environment.

V2X (Vehicle-to-Everything) standards have been initially designed for vehicles to exchange basic status and positioning information through beacons (CAMs – Cooperative Awareness Messages [3] or BSM – Basic Safety Messages [4]). However, the research community [5] and standardization bodies are currently working to extend V2X communications so that vehicles and infrastructure nodes can also exchange local sensor information to improve their perception capabilities and the knowledge of the surrounding driving environment. For example, the ETSI Technical Committee on ITS is currently designing the V2X messages (known as Collective Perception Message or CPM) necessary for vehicles to exchange sensor information about the status and dynamics of detected objects. Another important aspect yet to be decided is the CPM generation rules that define when should vehicles exchange CPM messages. These generation rules will have a significant impact on the effectiveness of the collective perception service and on the wireless vehicular network. In fact, if vehicles exchange information about detected objects very frequently, they will significantly improve their perception capabilities and be able to detect their surrounding objects with higher accuracy. However, a too frequent exchange of CPM messages can also saturate the communications channel to the point that these messages cannot be transmitted, ultimately reducing the effectiveness of the collective perception service. Limited studies have been conducted to date on the impact that the CPM generation rules will have on the effectiveness of the collective perception service and the saturation of the wireless communications channel. This paper addresses this limitation and conducts an in-depth analysis of the performance and efficiency of different CPM message generation rules that are currently discussed at ETSI. These generation rules have been analyzed under different driving conditions using the networks simulator ns3. The conducted analysis provides useful information and interesting observations about the existing trade-off between perception and channel utilization.

II. RELATED WORK

Most of the existing collective perception studies have focused either on the sensor or communication technologies. For example, [6] and [7] were some of the first studies focused on analyzing different sensing and fusion techniques. In these

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two studies, the raw sensed information was directly exchanged between vehicles. Alternatively, Kim *et al*. [8] investigated the exchange of raw sensor data, processed metadata (e.g. lane information represented in the point cloud) and compressed data (e.g. images from camera sensor) for collective perception. The results show that the communication delay increases with the amount of data transmitted so unnecessary data should be avoided. To minimize the bandwidth required for collective perception and reduce the latency, [9] investigated the concept of sharing detected object data instead of raw sensor data. In this study, authors experimentally evaluate through field tests the transmission latency and range for different message sizes and rates. Günther *et al*. [10] extended the message concept proposed in [9] for collective perception with different containers in order to specify the detected object parameters, sensor configurations and the characteristics of the transmitting vehicle. This information is used by the receiving vehicle to perform the coordinate transformation and locate the detected objects. The efficiency of the proposed message is investigated with an obstacle avoidance scenario with two vehicles. The results shows that the proposed solution allows vehicles to detect earlier a possible obstruction and hence augments the reaction time to handle a potential safety risk. The collective perception message concept proposed in [10] was evaluated under different low traffic densities in [11] and high traffic densities in [12]. Both studies considered different priority queues and Decentralized Congestion Control (DCC) mechanisms [13]. These studies analyse the awareness ratio and channel load for scenarios with different CAVs market penetration rates. They conclude that collective perception or cooperative sensing increases the awareness of the driving environment but could also increase the network congestion. Suggestions were made by the authors to incorporate collective perception information in the existing CAM [3] or move collective perception messages from the control to a service channel [14]. Alternately, Gani *et al*. [5] analyze the advantages of jointly controlling the transmission rate and length of cooperative sensing messages rather than controlling them separately. The studies discussed so far focus mainly on V2V (Vehicle to Vehicle) communications. Wang *et al*. highlight in [15] the possibility to utilize V2I (Vehicle to Infrastructure) communications to support collective perception at lower CAVs penetration rates.

This study extends existing CP literature by providing an in-depth analysis of the performance and efficiency of different CPM generation rules under different traffic densities. The objective is to investigate the effectiveness of the CPM generation rules (i.e. the capacity of vehicles to accurately be aware of their surrounding driving environment), and also the communications overhead and CP-related redundancy that they generate. This analysis provides important information to further optimize the CPM generation rules so that the CP effectiveness can be maintained while reducing the communications overhead to avoid saturating the communications channel.

III. CPM Standardization

ETSI TC ITS WG1 is currently working on the standardization of the Collective Perception Service (CPS) through the work items DTS/ITS-00167 and DTR/ITS-00183. The current developments are described in the Technical Report in [16] that will serve as a baseline for the specification of CPS in ETSI TS 103 324. The document reports the CPM format and its Data Elements, and the current CPM generation rules. In addition, the document discusses on the use of message fragmentation and segmentation for large CPM messages, and the need to utilize multiple channels to avoid saturating the control channel.

The current structure of the CPM includes an ITS PDU header and 4 types of containers: one Management Container, one Station Data Container, one or more Sensor Information Containers, and one or more Perceived Object Containers (POCs) [16]. The ITS PDU header was specified in [17] and includes Data Elements such as protocol version, the message ID and the Station ID. The Management Container is mandatory and provides basic information about the transmitting vehicle, including its type and position. The position is used to reference the detected objects. The Station Data Container is optional and includes additional information about the transmitting vehicle, such as its speed, heading, or acceleration. Part of this information is also included in the CAM transmitted by the same vehicle, but it is also needed in the CPM. If this information was not included in the CPM, the transmitting vehicle dynamics would need to be estimated by the receiving vehicle from the last received CAM. This estimation could reduce the accuracy of the positioning and speed estimation of the transmitting vehicle and its perceived objects.

The Sensor Information Containers describe the sensing capabilities of the transmitting vehicle. The Sensor Information Containers are used by receiving vehicles to derive the areas that are currently sensed by nearby vehicles. A Sensor Information Container includes the ID of a sensor, its type (e.g. radar, lidar or a sensor fusion system) and its detection area, among other Data Elements. Up to ten Sensor Information Containers can be included in a CPM.

The POCs describe the dynamic state and properties of the detected objects. Each POC includes information about a detected object, including its object ID, the ID of the sensor that detected it, the time of measurement, the distance between the detected object and the transmitting vehicle in the XY-plane, and the speed and dimensions of the object, among others. A single CPM can include up to 255 POCs. Multiple POCs could report information about the same detected object but obtained with different sensors. Alternatively, the sensed information could also be fused and reported in a single POC. The first approach reduces the computational needs and processing delays at the transmitting vehicle but may increase the channel load and processing needs at the receiver.

IV. CPM Generation Rules

The CPM generation rules should define how often a CPM is generated by the transmitting vehicle and which information (detected objects and sensors information) is included in the CPM. Periodic and dynamic policies are being investigated and discussed as part of the ETSI standardization process.

The periodic policy generates CPMs periodically every *T_GenCpm*. In every CPM, the transmitting vehicle includes the information about all the objects it has detected. The CPM should be transmitted even if no objects are detected. The periodic policy is being used as a baseline in the standardization process to compare its performance and efficiency with more advanced policies such as the dynamic one. With the dynamic policy, the transmitting vehicle checks every *T_GenCpm* if the environment has changed and it is necessary to generate and transmit a new CPM. If it is, the vehicle also decides the objects that should be included in the CPM. A vehicle generates a new CPM if it has detected a new object, or any of the following conditions are satisfied for any of the previously detected objects:

1. Its absolute position has changed by more than 4m since the last time it was included in a CPM.
2. Its absolute speed has changed by more than 0.5m/s since the last time it was included in a CPM.
3. The last time the object was included in a CPM was 1 second ago.
4. It is classified as Vulnerable Road User (VRU) or an animal.

All new detected objects and those that satisfy at least one of the previous conditions are included in the CPM. In all the generated CPMs, the Management Container, the Station Data Container are included, but the Sensor Information Containers are added only once per second. If no object satisfies the previous conditions, a CPM is still generated every second, but only including the Management Container, the Station Data Container and the Sensor Information Containers. It should be noted that these CPM generation rules are an adaptation of the CAM generation rules [3] for detected objects. In addition, these generation rules are preliminary and only a first proposal (hence subject to possible changes in the final specifications) that must be now carefully analyzed to understand its road traffic and communication implications.

V. SCENARIO

This study evaluates the impact of the CPM generation rules through simulations using ns3 and SUMO. We have extended ns3 with a CPS component and different onboard sensors. The CPS component implements the periodic and the dynamic CPM generation rules. Two different periodic policies with 10Hz (*T_GenCpm*=0.1s) and 2Hz (*T_GenCpm*=0.5s) have been considered as a baseline in this study. In the dynamic policy, the *T_GenCpm* parameter has been set to 0.1s, so that the maximum CPM rate is 10Hz. The CPM size is dynamically calculated by the transmitting vehicle based on the number of containers in each CPM. The size of each container has been estimated offline using the current ASN.1 definition of the CPM [16]. To this aim, we have generated 10^4 standard-compliant CPMs and Table I reports the average size of containers that is used in this study. In our scenario, each vehicle is equipped with two on-board sensors [16]. Sensor 1 has 65m range and a field of view of ±40 degrees. Sensor 2 has 150m range and a field of view of ±5 degrees. The sensor shadowing effect (sensor masking) is implemented in the XY-plane. We assume that the sensors can detect only the vehicles that are in their Line-of-Sight (LOS) [15] and that the objects detected by the two sensors are fused.

The traffic scenario is a six-lane highway with 5km length and a lane width of 4 meters. We simulate two different traffic densities following the 3GPP guidelines for V2X simulations [18]. The high traffic density scenario (120veh/km) has a maximum speed of 70km/h, while the lower one (60veh/km) has a speed limit of 140km/h. For each traffic density, this study considers different speeds per lane. The speeds have been selected based on statistics of a typical 3-lane US highway obtained from the PeMS database [19]. Vehicles measure 5m x 2m. To avoid boundary effects, statistics are only taken from the vehicles located in the 2km around the center of the simulation scenario. The configuration of the scenario is summarized in Table II.

All vehicles are equipped with an ITS-G5 transceiver (100% penetration) and operate in the same channel. The propagation effects are modeled using the Winner+ B1 propagation model following 3GPP guidelines [18]. The communication parameters are summarized in Table III.

TABLE I. CPM CONTAINERS

CPM Container	Size
ITS PDU header Management Container Station Data Container	121 Bytes
Sensor Information Container	35 Bytes
Perceived Object Container	35 Bytes

TABLE II. SCENARIO

Parameter	Values	
	Low traffic density	High traffic density
Highway length	5km	
Number of lanes	6 (3 per driving direction)	
Traffic density	60 veh/km	120 veh/km
Speed per lane	140 km/h 132 km/h 118 km/h	70 km/h 66 km/h 59 km/h

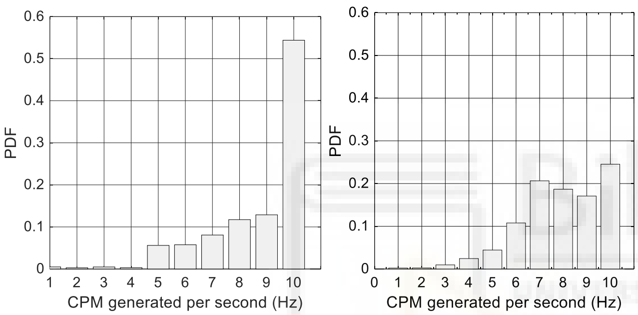
TABLE III. COMMUNICATION PARAMETERS

Parameter	Values
Transmission power	23dBm
Antenna gain (tx and rx)	0dBi
Channel bandwidth/carrier freq.	10MHz / 5.9GHz
Noise figure	9dB
Energy detection threshold	-85dBm
Data rate	6Mbps (QPSK 1⁄2)

VI. EVALUATION

A. Operation

Before analyzing the performance and efficiency of each CPM generation policy, it is necessary to better understand their operation. To this aim, we focus first on the dynamic policy. Figure 1 represents for this policy the Probability Density Function (PDF) of the number of CPMs transmitted per second per vehicle under the two traffic densities. The number of CPMs generated per vehicle depends on the number of detected vehicles (i.e. traffic density) and on their dynamics (e.g. an object is included in a CPM every 4m). The speed of vehicles is higher for low traffic densities than for higher ones. As a result, vehicles satisfy more frequently one of the 3 conditions specified in Section IV for the dynamic CPM generation rules, and vehicles generate more CPMs per second at low densities (Figure 1a) than at high densities (Figure 1b). However, not all vehicles generate CPMs at the same rate in a given traffic density scenario since the speed limit varies per lane (Table II). It is interesting to analyze with more detail the high traffic density scenario (Figure 1b). As previously mentioned, the higher the density the less CPMs are in general generated per vehicle since they travel at lower speeds. The vehicles that travel in the higher speed lane move at 70km/h or 19.4m/s. They will then change their absolute position by more than 4m every 0.21 seconds. Vehicles that detect this change generate then a CPM at 4.8Hz on average. However, Figure 1b shows that there are vehicles that transmit 6-10 CPMs per second. This is the case because a vehicle generates a CPM as soon as one of the vehicles it detects changes its absolute position by more than 4m. If the detected vehicles change their absolute position by more than 4m at different times, the transmitting vehicle will need to generate different CPM messages. This explains why CPM frequency rates as high as 10Hz are observed in the highest traffic density scenario (Figure 1b). It is also important to emphasize that the frequent transmission of CPMs reporting information about a small number of detected vehicles can result in a loss of efficiency due to a higher number of channel access attempts and redundant headers. Such efficiency might be improved by grouping in a single CPM the information of several detected vehicles in a short period of time.



(a) Low traffic density (b) High traffic density

Figure 1. PDF (Probability Density Function) of the number of CPMs generated per second and per vehicle with the dynamic policy.

Figure 2 represents the PDF of the number of objects included in each CPM for the periodic and dynamic CPM generation policies under the two traffic densities. The figure shows that the periodic CPM generation policies augment the size of CPMs since they include a higher number of detected objects per CPM. This is the case because the periodic policies always include in the CPM all the detected objects, while the dynamic policy selects the detected objects to be included in a CPM based on their dynamics. As the traffic density increases, the number of objects included in each CPM increases with the periodic policies because more objects (i.e. vehicles in our study) are detected. However, Figure 2 shows that the traffic density does not significantly affect the number of objects included in each CPM with the dynamic policy. This is the case because the speed of vehicles decreases with the traffic density. As a result, vehicles change their absolute position by more than 4m less frequently. So even if we detect more vehicles due to the higher traffic density, the status of a detected vehicle needs to be reported in a CPM less frequently. The obtained results clearly show the benefits of the dynamic policy since it can adapt the number of objects included in each CPM to the traffic density and speed.

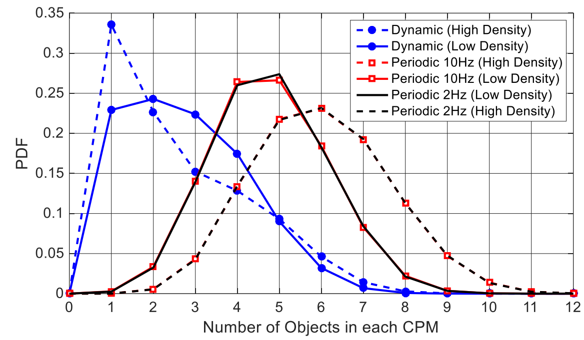


Figure 2. PDF (Probability Density Function) of the number of objects included in each CPM with the dynamic and periodic policies.

B. Communications performance

This section evaluates the impact of the CPM generation policies on the communications performance. To this aim, Table IV shows the average CBR (Channel Busy Ratio) experienced when implementing each CPM generation policy under the two traffic densities. The CBR is measured by each vehicle every second. The CBR is a measure of the channel load, and it is defined as the percentage of time that the channel is sensed as busy. A high CBR value indicates that the channel is very loaded and hence risks saturating. If this happens, the communications performance degrades and the packet delivery ratio decreases [20]. Table IV shows that the periodic policy operating at 2Hz is the one generating the lowest channel load. On the other hand, the periodic policy at 10Hz generates the highest channel load. The dynamic policy generates intermediate channel load levels (Table IV) in line with the results depicted in Figure 1 and Figure 2. These results showed that the dynamic policy generates between 4 and 10 CPMs per second, approximately, and reduces the number of objects per CPM compared to the periodic policies. Consequently, the dynamic policy increases the channel load compared to a periodic policy at 2Hz, but decreases it compared to the periodic policy at 10Hz. Table IV shows that the channel load and CBR increase with the traffic density. However, lower increases are observed with the dynamic policy. In particular, an increase in the traffic density augments the CBR experienced by the dynamic policy by a factor of 1.6, whereas it increases by factors of 2.1 (2Hz) and 1.9 (10Hz) for the periodic policies. This is again due to the same trend observed in Figure 2. When the traffic density increases, the speed of vehicles decreases and vehicles change their absolute position by more than 4m less frequently. As a result, vehicles generate less CPM messages, and the CBR degradation with the traffic density is lower for the dynamic policy than the periodic ones.

TABLE IV. AVERAGE CBR (CHANNEL BUSY RATIO)

Policy	**Traffic density**	**CBR**
Periodic at 2Hz	Low	5.6 %
	High	11.9 %
Periodic at 10Hz	Low	25.6 %
	High	49.6 %
Dynamic	Low	19.2 %
	High	31.7 %

The channel load or CBR has an impact on the PDR (Packet Delivery Ratio). The PDR is defined as the probability of successfully receiving a CPM as a function of the distance between the transmitting and receiving vehicles. Figure 3 plots the PDR of the periodic and dynamic CPM generation policies under the two traffic densities. The degradation of the PDR with the distance is due to the radio propagation effects. The PDR can also be degraded due to packet collisions or interference when the channel load is high. This effect is highlighted in Figure 3 where the arrows indicate the degradation of the PDR as a result of an increase of channel load and packet collisions when the traffic density increases. Table IV already showed how the channel load increases with the traffic density. The resulting PDR degradation observed in Figure 3 is hence a consequence of the trends observed in Table IV. Following these trends, Figure 3 shows that the periodic policy operating at 2Hz achieves the highest PDR and the policy at 10Hz the lowest one. Figure 3 also highlights that the dynamic policy achieves a balance between the two periodic policies. However, it is yet to be seen whether the dynamic policy could improve the network performance and increase the PDR by avoiding the transmission of certain CPM messages without degrading the perception capabilities of vehicles.

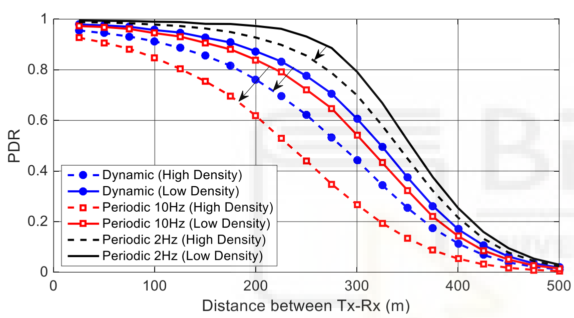


Figure 3. PDR (Packet Delivery Ratio) as a function of the distance between transmitter and receiver.

C. *Perception capabilities*

This section analyzes the perception capabilities of vehicles as a result of the different CPM generation policies. To this aim, we define the Object Awareness Ratio as the probability to detect an object (vehicle in this study) through the reception of a CPM with its information in a time window of one second. We consider that an object is successfully detected by a vehicle if it receives at least one CPM with information about that object per second. Figure 4 depicts the average Object Awareness Ratio as a function of the distance between the detected object and the vehicle receiving the CPM. The results are shown for the periodic and dynamic policies and the two traffic densities. The results obtained show that all policies achieve a high object awareness ratio (higher than 0.989) up to 350m. Beyond 350m, the awareness ratio degrades under higher densities for the dynamic policy and the periodic policy at 10Hz as a result of the higher CBR (Table IV) and lower PDR levels (Figure 3). On the other hand, Figure 4 shows that from 350m a higher degradation of the awareness ratio is observed for the periodic policy at 2Hz under low traffic densities. This is due to the fact that at such distances the propagation effect becomes dominant when the traffic density is low (there are less packet collisions). All CPM generation policies experience the same degradation due to the propagation since it is not dependent on the channel load. However, propagation loses affect more negatively the Object Awareness Ratio for the periodic policy at 2Hz since this policy transmits less CPMs.

The value of collective perception or cooperative sensing depends on how timely or fresh is the information received about the detected objects. A vehicle cannot base its driving decision on outdated information. Figure 5 plots the time difference between received CPMs with information about the same object or vehicle. The metric (referred to as the time between object updates) is represented as a function of the distance between the object and the vehicle receiving the CPMs for the low traffic density scenario. It is important to emphasize that the CPMs including information about the same object or vehicle might be transmitted by different or multiple vehicles. Figure 5 shows that all CPM generation policies provide object updates below 0.1s up to 200m approximately. This time value is reduced to 0.03s with the dynamic policy that can provide updates nearly as frequently as the periodic policy at 10Hz while better controlling the channel load (Table IV) and improving the communications performance (Figure 3). This is important to ensure the stability and scalability of the vehicular network that supports the implementation of collective perception. Similar trends have been observed under high traffic densities, but with even lower average time between object updates. The obtained results show that in general all CPM generation rules provide very frequent updates about detected objects. However, we have seen in Table IV and Figure 3 that the CPM generation policies can generate non-negligible channel load levels that can degrade the communications performance and impact the network's scalability. It is hence necessary to evaluate whether the current CPM generation policies generate unnecessary redundancy about the detected objects.

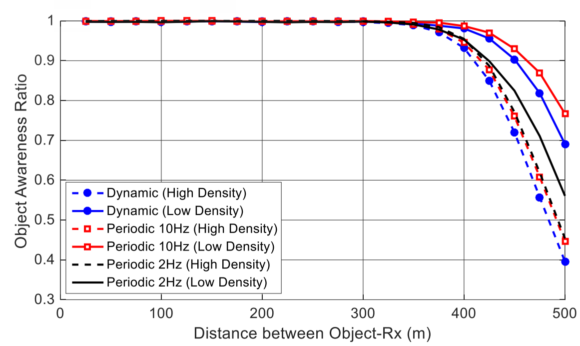


Figure 4. Object Awareness Ratio as a function of the distance between the detected object and the vehicle receiving the CPM.

Figure 6 illustrates the number of updates received per second about the same object through the reception of CPMs. This metric is referred to as detected object redundancy and is depicted in Figure 6 as a function of the distance between the object and the vehicle receiving the CPM. The degradation observed in Figure 6 with the distance is a direct consequence of the PDR degradation reported in Figure 3. Figure 6 shows that the periodic policy at 10Hz provides around 51 updates per second of the same object at short distances. The dynamic policy can reduce this value to around 30 updates per second and object without degrading the Object Awareness Ratio (Figure 4). In addition, the dynamic policy can reduce the channel load (Table IV) and improve the communications performance (Figure 3). Despite the gains observed with the dynamic policy, it is yet an open issue whether the still high redundancy levels observed in Figure 6 are necessary for a safe connected and automated driving or not. The dynamic policy could be modified to further decrease the redundancy and increase the robustness and scalability of the vehicular network as it is a key component to achieve the expected benefits of connected and automated driving.

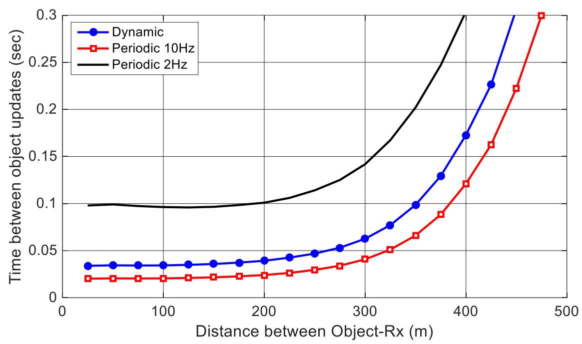


Figure 5. Average time between object updates as a function of the distance between the detected object and the vehicle receiving the CPM for the low traffic density scenario.

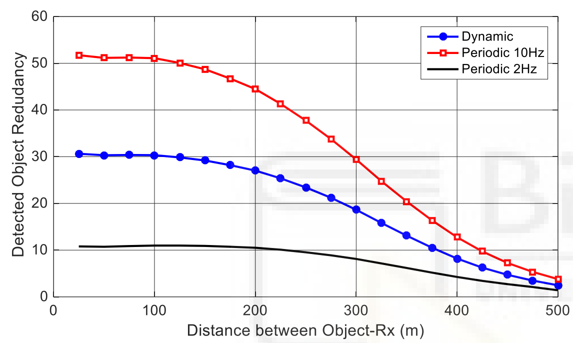


Figure 6. Detected object redundancy as a function of the distance between the detected object and the vehicle receiving the CPM for the low traffic density scenario.

VII. CONCLUSIONS

Collective perception or cooperative sensing can provide significant benefits to a safer connected and automated driving by improving the vehicles' perception of the environment through the exchange of sensor information. ETSI is now defining the standards to implement collective perception based on the exchange of information about the detected objects. This paper provides an in-depth evaluation of the operation, communications performance and perception capabilities of the different message generation rules under discussion. These rules define which objects should be transmitted in a CPM, and how often they should be transmitted. The obtained results show the existing trade-off between perception capabilities and communications performance (and network scalability). The conducted analysis has shown that the CPM generation policies that improve the perception capabilities generate higher channel load levels and hence have a higher risk to saturate the communications channel and render the network unstable. While some redundancy could benefit the detection of nearby objects, unnecessary redundancy could severely impact the performance of vehicular networks. The dynamic policy achieves an interesting balance between perception capabilities and communications performance. However, it is yet an open discussion whether the observed levels of redundancy are necessary or whether they could be further optimized to reduce any potential negative impact of the implementation of CPM in the stability and scalability of future V2X networks. These networks are fundamental to support connected and automated driving services.

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Annex A.2 Publication

IEEE Access

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Cooperative Perception for Connected and Automated Vehicles: Evaluation and Impact of Congestion Control

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ABSTRACT Automated vehicles make use of multiple sensors to detect their surroundings. Sensors have significantly improved over the years but still face challenges due to the presence of obstacles or adverse weather conditions, among others. Cooperative or collective perception has been proposed to help mitigate these challenges through the exchange of sensor data among vehicles using V2X (Vehicle-to-Everything) communications. Recent studies have shown that cooperative perception can complement on-board sensors and increase the vehicle's awareness beyond its sensors field of view. However, cooperative perception significantly increases the amount of information exchanged by vehicles which can degrade the V2X communication performance and ultimately the effectiveness of cooperative perception. In this context, this study conducts first a dimensioning analysis to evaluate the impact of the sensors' characteristics and the market penetration rate on the operation and performance of cooperative perception. The study then investigates the impact of congestion control on cooperative perception using the Decentralized Congestion Control (DCC) framework defined by ETSI. The study demonstrates that congestion control can negatively impact the perception and latency of cooperative perception if not adequately configured. In this context, this study demonstrates for the first time that the combination of congestion control functions at the Access and Facilities layers can improve the perception achieved with cooperative perception and ensure a timely transmission of the information. The results obtained demonstrate the importance of an adequate configuration of DCC for the development of connected and automated vehicles.

INDEX TERMS Cooperative perception, collective perception, cooperative sensing, message generation, CPM, connected automated vehicles, CAV, automated vehicles, autonomous vehicles, V2X, vehicular networks, C-ITS, ITS-G5, congestion control, DCC, ETSI.

I. INTRODUCTION

Automated vehicles use embedded sensors to drive autonomously with low or no human intervention. To this aim, the vehicle's planning system uses perception and localization data to determine the travel path and driving actions (e.g. lane changes, acceleration or braking) that are executed by the vehicle's control platform. For perception and localization, automated vehicles equip multiple exteroceptive sensors (e.g. lidars, radars and cameras) that locally perceive the driving environment [1]. This environment includes static elements (e.g. road shape and curvature, lane marks and trees) and dynamic ones (e.g. other vehicles, bicycles, pedestrians). Sensors for automated vehicles have significantly improved their perception range and detection accuracy over the last years [2]. However, the capabilities of these sensors can still be impaired due to the presence of obstacles, adverse weather conditions, or sensitivity to lighting conditions among other factors [3]. These limitations can negatively influence the safety and efficiency of automated vehicles. V2X (Vehicle-to-Everything) communications can reduce this negative impact and improve the perception or sensing capabilities of Connected and Automated Vehicles (CAVs) by facilitating the exchange of sensor data among vehicles. This process

The associate editor coordinating the review of this manuscript and approving it for publication was Maged Abdullah Esmail.

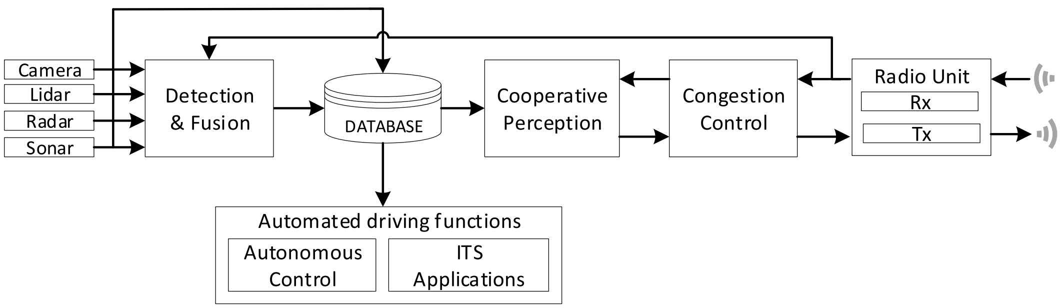

FIGURE 1. **Basic architecture of cooperative perception.**

is generally referred to as cooperative perception, collective perception or cooperative sensing [4], [5]. Figure 1 depicts the basic architecture for cooperative perception [6]. On-board sensors locally perceive the environment and perform the necessary processing, fusion and detection tasks to support the automated driving functions. The information gathered by the sensors is also used as an input for the cooperative perception component. This component selects the information to be exchanged among vehicles. For example, it decides which detected objects should be included in a cooperative perception message and how often these messages should be transmitted. Congestion control protocols may adapt the rate at which cooperative perception messages are generated and transmitted to control the communications channel load. It should be noted that the received cooperative perception messages are fused with the information obtained from the on-board sensors to improve and extend the vehicles' perception of the driving environment.

Cooperative perception enables vehicles to exchange their sensors' data. This provides vehicles with additional sensor data about the driving environment, including data beyond their on-board sensors' field of view (FoV). Cooperative or collective perception can also help improve the vehicles' sensor detection accuracy and increase the confidence about the detected objects. This is the case because vehicles can correlate and compare the information from their on-board sensors with sensor information gathered from nearby vehicles using V2X communications. Cooperative perception also helps mitigating the negative impact of adverse weather conditions or the negative effect of lighting conditions on the sensitivity.

Cooperative perception relies on V2X communications for vehicles to exchange sensor data. The development of V2X communications was initially focused on the so-called Day One Services [7]. These services include, among others, a basic cooperative awareness service where vehicles regularly broadcast their position, speed and basic status information through CAMs (Cooperative Awareness Messages) based on ETSI (European Telecommunications Standards Institute) standards [8] or BSMs (Basic Safety Messages) based on SAE (Society of Automotive Engineers) standards [9]. This basic cooperative awareness service improves the awareness of vehicles, but the information exchanged is limited and does not exploit the rich sensor data gathered by CAVs. ETSI [4] and SAE [5] have then recently launched activities to define new V2X standards to implement collective or cooperative perception for CAVs to exchange sensor data. ETSI has recently finalized a Technical Report to define the so-called Collective Perception Service (CPS). This service includes the definition of the Collective Perception Message (CPM) format and the generation rules to decide when a new CPM should be generated and what information it should include. These efforts highlight the industrial interest and potential of V2X communications to support the development and deployment of connected and automated vehicles. However, the work is still at its early stages, and has initially focused on drafting a framework to develop cooperative perception and define first CPM messages and generation rules. It is then necessary to better understand the operation of cooperative perception and optimize the related V2X communication protocols to maximize the effectiveness of cooperative perception while ensuring the network's scalability. This is important since exchanging sensor data significantly increases the communication channel load.

This study goes beyond the state-of-the-art and presents a dimensioning study that analyzes the performance and effectiveness of cooperative perception using V2X communications. The study first shows how cooperative perception mitigates the perception limitations of on-board sensors. The study then analyzes the impact of the market penetration rate and different sensor configurations on the operation and performance of cooperative perception. This analysis shows that cooperative perception can significantly increase the communication channel load and activate the operation of congestion control protocols. The study investigates then the impact of these protocols on the performance and operation of cooperative perception. The study is based on ETSI's Decentralized Congestion Control (DCC), one of the most important congestion control frameworks to date that operates across multiple layers of the V2X communication protocol stack. The study demonstrates that using congestion control protocols only at the Access layer augments the latency (or information age) of cooperative perception messages. This negatively impacts connected automated driving that requires low latency for a safe driving. This study demonstrates then for the first time that this challenge can be addressed through the combination of congestion control functions at the Access and Facilities layers. This combination increases the perception and reduces the latency through the dynamic adaptation of the rate at which cooperative messages are generated and transmitted.

II. STATE OF THE ART

Perception of automated vehicles has advanced significantly over the past years [2], [10], [11]. However, there are still relevant perception challenges that need to be solved [3], [11]. For example, the detection accuracy under poor weather and lighting conditions must be improved to reduce uncertainty. This is particularly the case of lidars and cameras. Lidar sensing can be restricted by high refraction and reflection caused by dense fog, smoke and rain [3]. Also, high sun angles may increase the noise level in lidar pulses which will affect the perception. In addition, their detection range depends on the reflectivity of the objects that are reached by the laser beams [2]. Cameras are very good for classifying objects and provide additional information about the environment (color, texture, etc.) [3]. However, cameras also see their performance degrade under adverse weather conditions and are very sensitive to lighting conditions. In addition, they require intensive and diverse training data for their AI-based image processing [10]. Moreover, velocity and distance information to detected objects cannot be directly measured with cameras but must be calculated [3]. Radars perform better than lidars and cameras in poor weather conditions (rain, snow, fog, etc.) [3], and some radars can detect objects at 250 m distance [12]. However, they provide lower resolution than lidars, and their field of view is limited [3]. In fact, the range and speed resolution of a radar is determined by its bandwidth. Products available on the market provide accuracies of 10 cm up to 1% to 5% of the distance to the object [12]. Radars also suffer from multipath fading, which reduces the accuracy of the detected objects [3]. The perception of automated vehicles also needs to be improved in complex urban environments. In particular, it is necessary to improve the accuracy, certainty and reliability of the sensors' perception. This is especially the case due to the presence of occluding objects (e.g. other vehicles or buildings) that can limit the sensor's range [11]. Lidar, radar and cameras can only work under Line-of-Sight (LOS) conditions. All these challenges and constraints limit the perception capabilities of automated vehicles that exclusively rely on their on-board sensors. This can in turn impact their safety and driving efficiency.

Cooperative perception has been proposed to improve the perception capabilities of CAVs. Cooperative perception makes use of V2X communications so that vehicles can exchange sensed data. Most of the studies conducted to date consider that vehicles exchange information about the detected objects (e.g. their position, speed and size). Recent studies have analyzed what information should be exchanged about detected objects in cooperative perception. Günther *et al*. propose in [13] to include in cooperative perception messages not only basic information about detected objects (e.g. their speed and position) but also information about the on-board sensors and the characteristics of the transmitting vehicle. This allows the receiving vehicles to understand the capabilities of the transmitting vehicles and better identify free-space and unknown areas. The authors show in [13] that their proposal allows earlier detection of possible obstructions and hence augment the driver's reaction time in the presence of a potential safety risk. The proposal from [13] was evaluated in [14]. This study compares the perception achieved when the information about the detected objects is attached to existing CAMs or is transmitted in separate messages that are transmitted following the CAM generation rules. Authors of [15] propose a message format to decrease the transmitted information without affecting the accuracy of the perception system. The proposed format includes information about the correlation and higher order derivatives (e.g. the acceleration or yaw rate) of the detected objects, and this information is transmitted less frequently. The work in [16] proposes and evaluates different content control schemes for cooperative perception. The study concludes that cooperative perception should prioritize the transmission of content related to objects that are located farther away from the transmitting vehicle but near the edge of its on-board sensor range in order to optimize the tracking error. The authors show that coupling this proposal with a multiplicative decrease and additive increase transmit rate control can also control the communication channel load and improve the channel utilization.

Controlling the channel load is critical for the performance of V2X communications and hence for the effectiveness of cooperative perception. Recent studies have then focused on optimizing the exchange of information about detected objects in cooperative perception. For example, the work in [17] proposes the concept of value-anticipating networking so that an object is included in a cooperative perception message and transmitted only if the transmitter estimates that it could have value for potential receivers. This approach reduces the transmission rate of less valuable information and can help control the channel load in congested scenarios. The challenge is to obtain an accurate estimation of the value of the information. This challenge has been partially addressed in a recent study by the same authors in [18] where they propose the use of deep reinforcement learning to select the data to transmit. A similar concept was proposed in [19] where authors present a method for each vehicle to dynamically adapt the message transmission rate taking into account the area covered with their sensors and that is not covered by nearby vehicles. In [20], authors evaluate the impact of congestion control on cooperative perception. To this aim, authors consider the Reactive approach that is part of ETSI's DCC framework at the Access layer, and evaluate the impact of considering different DCC Profiles (or DPs) for the collective perception messages. This study was one of the first to consider the impact of congestion control.

The authors demonstrate that congestion control does impact the performance and operation of cooperative perception, and should hence be carefully designed. This should include the congestion control functions at the Access layer that were the focus of the study in [20]. However, it should also consider those functions that control and adapt the generation rate of cooperative perception messages, since the message rate has a notable impact on the communication channel load. The same authors recently proposed in [21] message generation rules for cooperative perception based on the dynamics of vehicles. These generation rules decide when a new cooperative perception message should be created and what should be its content. The message generation rules proposed in [21] have been adopted within the ETSI Technical Report[1] for collective perception [4]. These generation rules were evaluated in detail in [22] where authors found that they can frequently generate messages with a small number of objects. This increases the channel load since packets with a small payload create a relatively high overhead due to the message headers. The study also found that the ETSI generation rules for cooperative perception can significantly increase the number of updates received per second about the same object. It is unclear whether this really benefits perception while it significantly increases the communication channel load. Similar conclusions were reached by authors of [23], [24] and [25] that also argue for the need to control the information exchanged with cooperative perception in order to avoid exceeding the communication channel capacity.

Existing studies demonstrate the industrial interest and potential of cooperative perception to improve connected automated driving. However, a more comprehensive understanding of cooperative perception is necessary for its correct dimensioning and configuration. This is exactly the objective of this study that first looks into the impact of the type of sensors and market penetration rate on cooperative perception. This study analyzes then in detail the impact that V2X congestion control has on cooperative perception. This is important since congestion control protocols modify the transmission of messages, and this can significantly impact the effectiveness of cooperative perception. The study demonstrates for the first time how a careful combination of congestion control functions at different layers of the protocol stack can improve the performance of cooperative perception.

III. COLLECTIVE PERCEPTION SERVICE

ETSI has recently approved the Technical Report [4] that proposes the Collective[2] Perception Service (CPS) and that will serve as a baseline for the Technical Specification TS 103 324. The following subsections describe the current Collective Perception Message (CPM) format and the CPM generation rules defined in [4] and that are used in this study.

A. COLLECTIVE PERCEPTION MESSAGE

The CPM is a broadcast message that includes an ITS (Intelligent Transport System) PDU (Protocol Data Unit) header and 5 types of containers: a Management Container (MC), a Station Data Container (SDC), a Sensor Information Container (SIC), a Perceived Object Containers (POC) and a Free Space Addendum Container (FSAC). It also contains a data element that specifies the current number of perceived objects. This number does not necessarily match with the number of objects included in the CPM because all objects are not included in all CPMs, as explained in the next subsection. The main containers and data elements are next described.

1) ITS PDU HEADER

The ITS PDU header was specified in [26] and includes data elements such as the protocol version, the message ID and the station ID.

2) MANAGEMENT CONTAINER

The MC is mandatory in the CPM and contains basic information about the transmitter, including its type (e.g. vehicle or RSU) and position. The MC also includes an optional container to inform about whether the data of a CPM has been split up into multiple messages due to message size constraints.

3) STATION DATA CONTAINER

The SDC is optional and includes additional information about the originating vehicle or RSU. The SDC can include the Originating Vehicle Container (OVC) or the Originating RSU Container (ORC) depending on whether a vehicle or RSU generates and transmits the CPM. The OVC describes the vehicle data elements, such as the heading, speed and angle, and its size. The ORC includes information such as the Intersection Reference ID or Road Segment ID. This information is useful for the receiver to match the received objects to the defined intersection or road segment.

4) SENSOR INFORMATION CONTAINER

The SIC is optional and describes the sensing capabilities of the transmitter. The SIC is used by the receiver to derive the areas that are currently sensed by the transmitter. For each sensor, the SIC includes data elements such as the sensor ID, sensor type (e.g. radar, lidar or a sensor fusion system) and its detection area. The SIC can optionally specify for each sensor its Free Space Confidence, which is the isotropic free space confidence that can be assumed for its entire detection area. When sensor fusion is not used, the SIC includes the capabilities of each of the on-board sensors; the CPM can report about up to 128 sensors. When using sensor fusion, all the sensors capabilities are combined and reported in the SIC as a single sensor.

[1]This Technical Report has been recently approved and will be used as a starting point for the ETSI Technical Specification of collective perception.

[2]ETSI generally refers to cooperative perception as collective perception. We will then maintain the term collective perception in this section and when referring to ETSI content or discussions.

5) PERCEIVED OBJECT CONTAINER

The POC is set optional and describes the dynamic state and properties of the detected objects. The POC contains information about up to 128 detected objects. For each object, the following data elements are included in the POC: (1) the object ID that identifies the object and can be used for tracking purposes; (2) the Time of Measurement that provides the time difference between the message generation time and the object measurement time[3]; (3) the IDs of the sensors that have detected the object; (4) the position, speed, acceleration and size of the object (among other fields); (5) the confidence associated to the object; (6) and its classification (vehicle, person, animal, other). These and other data elements provide a detailed description of the detected object and enable the receiver to coordinate and track the detected object in a three-dimensional space.

6) FREE SPACE ADDENDUM CONTAINER

The FSAC is optional and describes the free space areas within the sensor detection areas. In addition, it includes their associated confidence levels. This information can be used by the receiver to better estimate the free space areas around the transmitting vehicle.

B. CPM GENERATION RULES

The CPM generation rules define how often a vehicle should generate a CPM and what information should be included in each CPM. A vehicle should check every *T_GenCpm* if a new CPM should be generated. *T_GenCpm* should be set between 100 ms and 1000 ms. It is important to highlight that the DCC can adapt *T_GenCpm* based on the channel load as we will describe in detail in the next section. A vehicle should generate a new CPM if it has detected a new vehicle, or if any previously detected vehicles satisfy any of the following conditions:

- its absolute position has changed by more than 4m since the last time its data was included in a CPM;
- its absolute speed has changed by more than 0.5m/s since the last time its data was included in a CPM;
- its absolute velocity has changed by more than 4° since the last time its data was included in a CPM;
- the last time it was included in a CPM was 1 (or more) seconds ago.

A vehicle includes in a new CPM all new detected vehicles and those previously detected vehicles that satisfy at least one of the previous conditions. The CPM generation rules prioritize then the transmission of information about the detected vehicles that are moving faster or have higher acceleration. These vehicles are included in CPMs more frequently so that other vehicles can have an accurate and updated knowledge of the driving environment.

We should note that a vehicle generates a CPM every second even if none of the detected vehicles satisfy any of the previous conditions. In this case, the CPM will not contain the Perceived Object Container, but only the Management Container, the Station Data Container, and the Sensor Information Containers. In addition, the SIC is only included in a CPM once per second since the sensor information does not change.

[3] This information is useful to accurately compute the information age for each object at the receiver.

IV. DECENTRALIZED CONGESTION CONTROL

Cooperative perception relies on the V2X exchange of information about detected objects. Its effectiveness depends on the correct reception of the exchanged V2X messages. The performance of V2X communications is highly influenced by the communication channel load since high channel load levels increase the risk of packet collisions. Vehicular networks integrate congestion control algorithms to control the channel load and avoid channel congestion [27]. These protocols can modify the rate or the power at which messages are transmitted and even drop packets. Congestion control algorithms can then alter the transmission of V2X messages and could then impact the effectiveness of cooperative perception. This paper studies this impact in detail using the Decentralized Congestion Control (DCC) solution defined by ETSI. This is one of the most complete solutions to control congestion in vehicular networks since it defines DCC components and functions at all relevant layers of the protocol stack.

A. ITS COMMUNICATIONS ARCHITECTURE

DCC is implemented over the ITS Communications Architecture defined by ETSI [28] and illustrated in Figure 2. This architecture follows the principles of the OSI (Open System Interconnection) model and is divided in different layers. The Access layer covers the PHY (Physical) and MAC (Medium Access Control) layers of the protocol stack. It controls the access to the radio channel and enables the wireless transmission and reception of information. The Transport & Network layer is used to multiplex messages from different services and route them from source to destination nodes. The Facilities layer includes components and services, such as the Collective Perception Service, that are used to support V2X applications. Applications are implemented on the top and are abstracted from the underlying protocols. The transversal

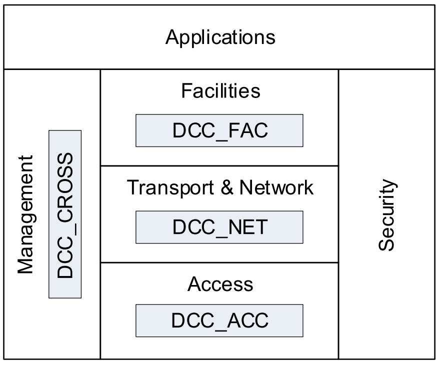

FIGURE 2. ETSI ITS Communications Architecture with DCC components.

Management layer is in charge of the management of the communications and the protocol stack. The Security layer provides the necessary security services, such as privacy or encryption.

CPMs are generated by the Collective Perception Service at the Facilities layer and sent down to the lower layers for their transmission. At the Transport & Network layer, CPMs make use of the BTP (Basic Transport Protocol) that multiplexes messages from different applications/services. In the same layer, the GeoNetworking protocol configures the transmission of the CPM in broadcast mode to all 1-hop neighboring nodes. At the Access layer, CPMs can be transmitted using the ITS-G5 [29] radio access technology. ITS-G5 is an adaptation of IEEE 802.11p, which was specifically designed for vehicular environments. IEEE 802.11p uses OFDM (Orthogonal Frequency Division Multiplexing) with a channel bandwidth of 10 MHz. It supports data rates from 3 to 27 Mbps using coding rates of 1/2, 2/3 or 3/4 (convolutional coding) and BPSK (Binary Phase Shift Keying), QPSK (Quadrature Phase Shift Keying), 16-QAM (16-Quadrature Amplitude Modulation) or 64-QAM modulations. The basic radio channel access method of IEEE 802.11p is known as Carrier Sense Multiple Access with Collision Avoidance (CSMA/CA). In CSMA/CA, a node must sense the radio channel before transmitting a packet. If the channel is sensed as idle, the node can start its transmission. If the channel is sensed as busy, the node defers its transmission until the end of the current transmission. At the end of the channel busy period, the node waits for a random backoff time. This backoff is used to minimize collisions between multiple nodes that also deferred their transmission since they also detected the channel as busy. The node decreases the backoff time when it senses the channel as idle and can start its transmission when its backoff time reaches zero. To provide different channel access times to different types of packets, IEEE 802.11p makes use of EDCA (Enhanced Distributed Channel Access) that differentiates 4 access categories. Each category has different channel access parameters (e.g. backoff times).

B. DCC FRAMEWORK

The generation and transmission of messages using the ITS Communications Architecture is controlled by DCC. DCC is a cross-layer function that spans over multiple layers of the protocol stack. In particular, ETSI has defined DCC_ACC, DCC_NET, DCC_FAC and DCC_CROSS components (see Figure 2). The DCC_ACC [30] component is in the Access layer and has been the target of most of the research conducted to date. It operates as a gatekeeper to control the traffic that is effectively transmitted by each vehicle. DCC_NET [31] is optional and implemented at the Networking & Transport layer. It enables vehicles to exchange information about the channel load they sense so that each vehicle is aware of the channel load experienced by its one-hop and two-hop neighbours. The Technical Specification that defines DCC_FAC [32] is still a draft and has not been approved yet. In the current draft, DCC_FAC is defined as optional and is implemented at the facilities layer when considered. It controls the number of messages generated by each application/service within each vehicle. The control takes into account the messages' traffic classes or DCC profiles (DPs). Thus, DCC_FAC distributes access to the channel among the different applications/services within each vehicle.

DCC_CROSS [33] defines the necessary management support functions for DCC and the required interface parameters between the DCC management entity and the DCC entities in the Facilities, the Networking & Transport and the Access layers. For all DCC components, the upper limits of the maximum transmission duration and minimum time interval between two consecutive transmissions are defined in ETSI EN 302 571 [34]. In this study, we analyze the impact of DCC_ACC and DCC_FAC on cooperative perception since they contain the main mechanisms that control congestion and that can affect the V2X communications performance.

C. DCC ACCESS

The DCC_ACC component is located in the Access layer. It controls the traffic at the Access layer and acts as a gatekeeper. To this aim, it adapts the amount of time that each vehicle can access the channel as a function of the channel load. The channel load used as input for the algorithm can be the one locally measured by a vehicle or the one provided by DCC_NET if vehicles share their channel load measurements. ETSI defines in [30] the DCC_ACC component for ITS-G5. It makes use of Prioritization, Queuing and Flow Control, as described below.

Prioritization: The packets that are received by the DCC Access component from the upper layers are first classified according to their traffic class. The traffic class is defined by the Facilities layer to provide different priority levels to different types of messages. Four different traffic classes are differentiated by DCC Access and mapped to four DCC profiles (DPs): DP0, DP1, DP2 and DP3, where DP0 has the highest priority. At the lower layers, these DCC profiles are mapped to the EDCA access categories of ITS-G5 [35].

Queuing: DCC Access implements 4 different queues, one for each traffic class or DCC profile. Each queue follows a first-in-first-out (FIFO) scheduling policy so that the packet that has been waiting longer in the queue is transmitted first. The DCC Access queuing mechanism drops those packets that have been waiting in the queue for a time longer than their lifetime. When a queue is full, no more packets are accepted.

Flow control: Flow control is applied to de-queue packets from the DCC queues and send them to the lower layers for their radio transmission. Packets with higher priorities are de-queued first. A packet is only de-queued if there is no packet with a higher priority waiting in its corresponding queue. As a result, lower priority packets can suffer from starvation and never be transmitted.

DCC Access defines in [30] two approaches to control the rate of packets transmitted per vehicle: Reactive and Adaptive. Both approaches adapt the time between consecutive packet transmissions based on the channel load or CBR (Channel Busy Ratio). The CBR is defined as the percentage of time that the channel is sensed as busy. These two approaches are described below.

1) REACTIVE APPROACH

The Reactive approach makes use of a state machine for flow control. Each state is mapped to a range of CBR values and to a time T_{off}. T_{off} is the minimum time interval allowed between message transmissions for each vehicle and is different for each state. Therefore, T_{off} is the inverse of the maximum message transmission rate allowed per vehicle in each state. When the CBR changes, the Reactive approach switches to the corresponding state, changing the minimum T_{off} and maximum message rate allowed per vehicle. As a result, vehicles dynamically adapt their message rate to the CBR.

The Restrictive state is the state associated with the highest CBR and the Relaxed state is associated to the lowest one. A number of intermediate states called *Active states* can also be defined. Each state can only be reached by a neighbouring state. Table 1 shows the mapping of CBR values to states and T_{off} reported as Informative Annex in [30]. This table is derived considering that the packet duration T_{on} is below 0.5 ms. Other configurations are possible but we have used the one shown in Table 1 because it is the one adopted by the C2C-CC (Car-to-Car Communication Consortium) [36].

TABLE 1. Mapping of CBR values to states and T_{off} for T_{on} < 0.5 ms [30].

State	CBR	Packet rate	T_{off}
Relaxed	< 30%	20 Hz	50 ms
Active 1	30% to 39%	10 Hz	100 ms
Active 2	40% to 49%	5 Hz	200 ms
Active 3	50% to 65%	4 Hz	250 ms
Restrictive	> 65%	1 Hz	1000 ms

2) ADAPTIVE APPROACH

The Adaptive approach uses a linear control process for flow control. The process is designed so that each vehicle adapts its packet transmission rate in order for the channel load to converge to a target value $CBR_{target} = 68\%$. To this aim, every 200 ms each vehicle adapts the parameter δ that represents the maximum fraction of time that a vehicle is allowed to transmit. The parameter δ is updated based on the difference between the current CBR sensed and the target CBR using the following equation:

$$\delta = (1-\alpha)\cdot\delta + \delta_{offset} \quad (1)$$

where

$$\delta_{offset} = \beta \cdot \left(CBR_{target} - CBR\right) \quad (2)$$

and

$$G^{-}_{max} \leq \delta_{offset} \leq G^{+}_{max} \quad (3)$$

The values of the parameters are defined in [30] as $\alpha = 0.016$, $\beta = 0.0012$, $G^{-}_{max} = -0.00025$ and $G^{+}_{max} = 0.0005$.

The protocol computes then the time between packet transmissions (T_{off}) after every transmission. To this aim, it takes into account the duration of the current packet (T_{on}) and the fact that $0.025\text{s} \leq T_{off} \leq 1\text{s}$:

$$T_{off} = \frac{T_{on}}{\delta} \quad (4)$$

It is also recommended to update T_{off} when δ is updated. Different studies have demonstrated that the Adaptive approach is able to converge to a stable solution in steady state [37].

D. DCC FACILITIES

DCC Access controls the total amount of messages that a vehicle can transmit per second. DCC at the Facilities layer (DCC_FAC) controls the number of messages that each application/service can generate [32] to satisfy the DCC Access limit imposed to each vehicle. To this aim, the DCC_FAC makes use of the DCC Access limit, the message size and the message interval from each application/service. The current ETSI draft that defines the DCC_FAC component calculates the minimum interval $T_{off\,min\,ij}$ for each application/service with index j and traffic class with index i. Based on this minimum interval, each vehicle proportionally distributes the channel resources to each application/service and traffic class. Distributing the channel resources with ITS-G5 is equivalent to distributing the channel access time. To perform this distribution, each vehicle estimates for each application/service j and traffic class i, the average message duration $\overline{T_{on\,ij}}$ and the average message interval $\overline{T_{off\,ij}}$ from the latest messages. The average message duration can be simply calculated as the ratio between the average message size of each application/service j and traffic class i and the data rate (by default, the data rate is set to 6 Mbps [35]). Then, the average channel resources consumed by each application/service can be estimated as:

$$\overline{CRE}_{ij} = \frac{\overline{T_{on\,ij}}}{\overline{T_{on\,ij}} + \overline{T_{off\,ij}}} \quad (5)$$

Using equation (5), the total channel resources CR_i from all applications/services of traffic class i can be calculated as:

$$CR_i = \sum_j \overline{CRE}_{ij} \quad (6)$$

The channel resources CBR_a that the vehicle can use depends on the current channel load and the specific DCC Access algorithm. For the Adaptive approach, $CBR_a = \delta$, i.e. the maximum fraction of time that a vehicle is allowed to transmit. However, for the Reactive approach, $CBR_a = 1/T_{off}$, i.e. the maximum number of messages that the vehicle can transmit per second. CBR_a is used by DCC Facilities as an input to distribute the available channel resources among the different traffic classes. The traffic class with the highest priority is TC_0, so the available channel resources for this traffic class ACR_0 is set equal to CBR_a. If traffic class TC_0

does not consume all the available channel resources for the vehicle, the remaining resources are assigned to the next traffic class. As a result, ACR_i for traffic class i is calculated as:

$$ACR_i = \max(0, ACR_{i-1} - CR_{i-1}) \tag{7}$$

Equation (7) can be applied to both Reactive and Adaptive approaches at the DCC Access, but ACR_i represents a fraction of time for Adaptive and a message rate for Reactive since they use a different CBR_a.

DCC Facilities then identifies the channel resources ACR_{ij} that each application/service j belonging to the same traffic class i can use. To this aim, it takes into account the average channel resources consumed by each application/service calculated with equation (5):

$$ACR_{ij} = \frac{\overline{CRE_{ij}}}{CR_i} \times ACR_i \tag{8}$$

For the Adaptive approach, the minimum interval $T_{off\ min\ ij}$ for each application/service with index j and traffic class with index i can be then calculated as follows:

$$T_{off\ min\ ij} = \overline{T_{on\ ij}} \times \frac{1 - ACR_{ij}}{ACR_{ij}} \tag{9}$$

For the Reactive approach, ACR_{ij} is a message rate and the minimum interval $T_{off\ min\ ij}$ can be directly computed as[4]:

$$T_{off\ min\ ij} = \frac{1}{ACR_{ij}} \tag{10}$$

$T_{off\ min\ ij}$ is then used to adapt the minimum time interval between message generations of each application/service. To this aim, the time interval used to check the message generation rules of each application/service (e.g. *T_GenCpm* for CPMs or *T_GenCam* for CAMs) is set equal to its corresponding $T_{off\ min\ ij}$. As a result, the time interval between consecutive messages of each application/service is dynamically adapted to satisfy the DCC Access limits imposed to each vehicle.

We now illustrate the operation of DCC Facilities with an example in a scenario where vehicles transmit CAMs and CPMs with the same DCC profile. The average message size at the facilities layer is 200 Bytes for CAMs and 300 Bytes for CPMs, including the ITS PDU header and the payload at the Facilities layer. Additionally, 80 Bytes of headers are added by the corresponding protocols: 4 Bytes are added by the Basic Transport Protocol (BTP) [38], 40 Bytes by the GeoNetworking protocol [31], [39], 30 Bytes by the Medium Access Control (MAC) and 6 Bytes by the PHY layer of IEEE 802.11p [29]. The average message interval is 0.2 s for CAMs and 0.1 s for CPMs. Let's assume that DCC Facilities is combined with the Adaptive approach at DCC Access and that the total available channel resources per vehicle is $CBR_a = \delta = 0.005$. In this case, each vehicle can use 0.5% of the channel access time when using IEEE 802.11p or ITS-G5. We consider that vehicles transmit at a data rate of 6 Mbps. The average channel resources consumed by CAM and CPM messages can be estimated using equation (5) and are equal to $CRE_{CAM} = 0.0019$ and $CRE_{CPM} = 0.05$ respectively. We can then compute the total consumption of channel resources CR using equation (6): $CR = 0.0069$. Using equation (8), we can estimate the available channel resources for CAM ($ACR_{CAM} = 0.0013$) and CPM ($ACR_{CPM} = 0.0037$) messages. Finally, the minimum interval can be computed for CAMs as $T_{off\ min\ CAM} = 0.2763$s and for CPMs as $T_{off\ min\ CPM} = 0.1383$s following equation (9). We then adapt the generation rate of CPMs and CAMs at the Facilities layer so that $T\_GenCpm = T_{off\ min\ CPM}$ and $T\_GenCam = T_{off\ min\ CAM}$. A different solution would be obtained in this example if DCC Facilities was combined with the Reactive approach at DCC Access. The feedback provided by the Reactive approach is the maximum number of messages that the vehicle can transmit per second. Let's assume in this example that $CBR_a = 10$Hz. If we follow the same procedure to compute the minimum interval for CAMs and CPMs using equation (10) instead of (9), we obtain $T_{off\ min\ CAM} = 0.3706$s and $T_{off\ min\ CPM} = 0.137$s.

V. SCENARIO AND PARAMETERS

This study uses the network simulator ns-3 and the road mobility simulator SUMO. The ns-3 simulator implements the ITS-G5 V2X standard based on IEEE 802.11p. We extended ns-3 with a DCC Access module, a DCC Facilities module, a CPS component and different on-board sensors. The DCC Access module used in this study is described in [40] and publicly available. The CPS component implements the ETSI CPM generation rules defined in [4] and described in Section III. By default, all vehicles in the scenario are equipped with an ITS-G5 transceiver except when we analyze the impact of the Market Penetration Rate (MPR) on the effectiveness of cooperative perception. Vehicles transmit CAMs and CPMs. The CAM size is set equal to 350 bytes [41] and CAMs are generated following [8]. By default, the *T_GenCpm* parameter has been set to 0.1 s so the maximum CPM rate is 10 Hz. The CPM size is dynamically computed by the transmitting vehicle based on the number of containers in each CPM, the size of the containers reported in Table 2 and the number of objects included in a CPM.[5] Vehicles transmit messages using the 6 Mbps data rate (i.e. QPSK modulation with 1/2 code rate) and always use the same channel. The transmission power is set to 23 dBm and the packet sensing threshold to −85 dBm. Radio propagation is modeled using the Winner+ B1 propagation model following the 3GPP V2X guidelines [42]. This model was used for the simulation studies conducted during the V2X standardization process of the 3GPP. Other propagation models could have been used (e.g. [43]) but similar conclusions would

[4] This is currently not specified in the current draft of ETSI TS 103 141 but it is a change needed to combine the DCC Facilities algorithm with the Reactive approach at DCC Access.

[5] The Free Space Addendum Container is optional and has not been considered in this study.

TABLE 2. CPM containers.

CPM Container	Size
ITS PDU header + Management Container + Station Data Container	121 Bytes
Sensor Information Container	35 Bytes per sensor
Perceived Object Container	35 Bytes per object

TABLE 3. Communication parameters.

Parameter	Values
Transmission power	23 dBm
Antenna gain (tx and rx)	0 dBi
Channel bandwidth/carrier freq.	10 MHz / 5.9 GHz
Noise figure	9 dB
Energy detection threshold	-85 dBm
Data rate	6 Mbps (QPSK 1/2)

be obtained since our study is comparative in nature and a different model would affect similarly all configurations being tested.

Table 3 summarizes the main communication parameters. Unless specified, DCC is not enabled by default. When enabled, DCC Reactive and Adaptive are analyzed at the Access layer. We consider a queue length of 2 following [44] and different DCC profiles for the CPM since the standards have not specified them yet. The DCC profile for CPMs is set to DP2 or DP3 and the DCC profile of the CAM is set to DP2 following [45]. The DCC profile has an impact on the priority of the packets at the access layer. We have also implemented the current DCC Facilities defined by ETSI[6] and described in Section IV.

We implement three different sensor configurations shown in Table 4. In the forward sensors configuration, vehicles are equipped with two forward facing sensors following [4]. The 360° sensor configuration considers a single circular shape sensor with 360° field of view following [4]. The Tesla sensors configuration follows [46] and equips vehicles with seven sensors. In all sensor configurations, we assume that the sensors can detect only the vehicles that are in their line-of-sight. To this aim, we implemented in ns-3 a 2D sensor shadowing effect in the XY-plane that considers the occlusion caused by nearby vehicles. By default, this study assumes that the information about objects detected by multiple sensors is fused.

We consider a highway scenario with 5 km length and two driving directions. We simulated three traffic densities: low, medium and high as presented in Table 5. The low and medium traffic densities follow the 3GPP guidelines for V2X simulations [42] considering 6 lanes (3 in each direction) and a different speed per lane following statistics of a typical

[6] This implementation could be subject to modification since the standard has not been finalized yet.

TABLE 4. Sensor configurations.

Sensor	Specification	Range (m)	FOV (º)
Forward	Mid-range radar	65	±40
	Long-range radar	150	±5
360º	Circular radar	150	360
Tesla	Narrow forward camera	250	±15
	Radar	160	±15
	Main forward camera	150	±22
	Forward side cameras	80	±25-115
	Wide forward camera	60	±60
	Rear view camera	50	±115-180
	Rearward side cameras	100	±150-180

TABLE 5. Traffic scenarios.

Parameter	Traffic density scenarios		
	Low	Medium	High
Number of lanes	6	6	8
Vehicles per km	60veh/km	120veh/km	240veh/km
Speed per lane	140km/h 132km/h 118km/h	70km/h 66km/h 59km/h	50km/h for all lanes

3-lane US highway [47]. The high traffic density considers 8 lanes (4 in each direction) and a maximum speed of 50 km/h [47]. To avoid boundary effects, statistics are only taken from the vehicles located in the 2 km around the center of the simulation scenario.

VI. EVALUATION OF COOPERATIVE PERCEPTION

We first evaluate the perception capabilities of different sensor configurations without using cooperative perception. In this case, perception is limited by occluding objects. Figure 3 compares the object perception ratio experienced with the three sensor configurations under low and high traffic densities. The object perception ratio is defined as the probability of successfully detecting an object at a given distance. Sensors do not correctly detect a vehicle if their line-of-sight is occluded by other vehicles. Figure 3 shows that occluding vehicles can significantly degrade the perception

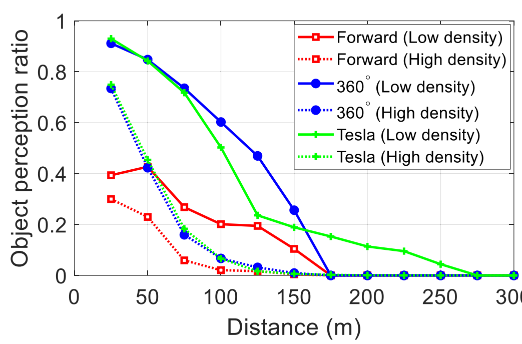

FIGURE 3. Object perception ratio achieved with different sensor configurations under low and high traffic densities.

capabilities, and the degradation increases with the distance and the traffic density. This is the case because both factors augment the probability that a vehicle blocks the sensors' line of sight. Figure 3 shows that the perception capabilities augment with the sensors' FoV and range. In this case, using forward sensors alone reduces the object perception ratio since these sensors cannot detect vehicles in all directions.

Cooperative perception can mitigate the occlusion problems illustrated in Figure 3 and increase the perception capabilities of connected automated vehicles. This is shown in Figure 4 that compares the average object perception ratio with and without using cooperative perception for the three different sensor configurations. When using cooperative perception, the metric is defined as the probability to successfully detect a vehicle within a time window thanks to the exchange of CPMs. We consider that a vehicle successfully detects an object if it receives at least one CPM with information about that object during the time window. The time window was set to 200 ms for the low traffic density scenario and to 300 ms for the rest of the scenarios. These values were chosen since they correspond to the time required by the CPM generation rules for a vehicle to send an update about a detected object considering the speed of the vehicles in each scenario. The metric is represented in Figure 4 as a function of the distance between the detected object and the vehicle receiving the CPM. Results in Figure 4 were obtained assuming 100% penetration rate of cooperative perception and that DCC is disabled. This is done so that Figure 4 focuses on the effect of the sensor configuration on the effectiveness of cooperative perception. We also assume that the vehicles fuse the information received from their multiple sensors. In this case, if multiple sensors detect the same object, the vehicle will only transmit once the information about the detected object.

Figure 4 clearly shows that cooperative perception significantly increases the perception capabilities of CAVs. In particular, it increases the distance at which objects can be detected compared to when only using the on-board sensors. Figure 4 shows that in these scenarios the sensor configuration does not significantly affect the object perception ratio when utilizing cooperative perception compared to when not utilizing it (Figure 3). In fact, the Tesla and 360° sensor configurations achieve similar perception rates, and the perception with the forward sensor configuration only slightly degrades at medium to large distances for low traffic densities (Figure 4a). This is the case because cooperative perception compensates the perception limitations of sensors. For example, a vehicle that uses only forward sensors can detect objects behind when using cooperative perception thanks to the CPMs received from other vehicles that detect these objects. We should note that the slight perception degradation observed in Figure 4 with the forward sensor configuration is reduced for higher traffic densities. This is the case because at higher densities more vehicles detect each object and cooperative perception can better compensate the limitations of the forward sensors.

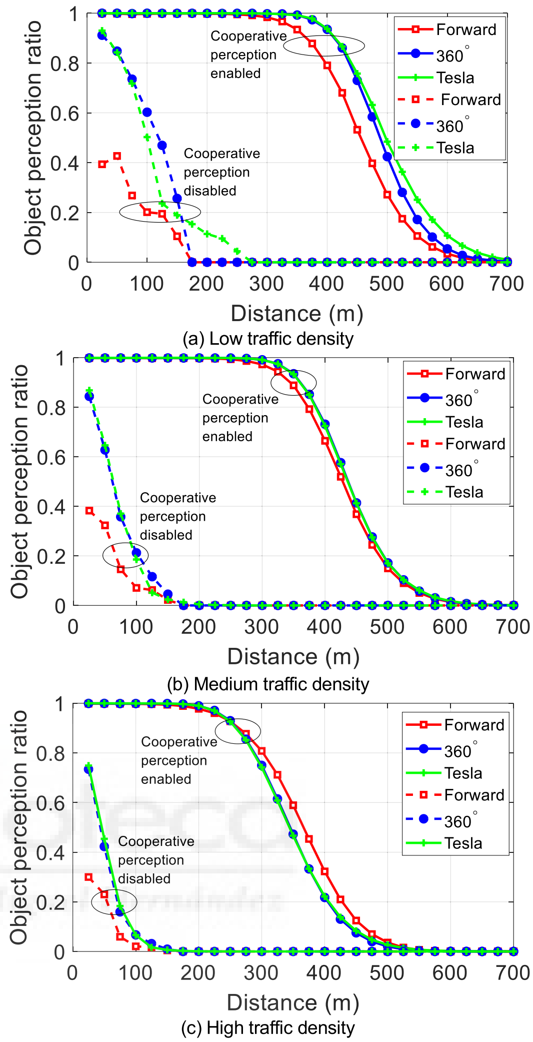

FIGURE 4. Object perception ratio under different traffic densities. When using cooperative perception, the x-axis represents the distance between the detected object and the vehicle receiving the CPM. When cooperative perception is not used, the x-axis represents the distance between the detected object and the vehicle detecting it with its sensors.

Figure 4 also reveals that the object perception ratio significantly decreases when the traffic density increases. This degradation is due to the increase in channel load and interferences at higher traffic densities. The interferences augment the packets losses due to packet collisions and degrade the PDR (Packet Delivery Ratio) as it can be observed in Figure 5. This figure also shows that the highest PDR under the highest traffic density is achieved with the forward sensor configuration. This is the case because each vehicle detects a lower number of vehicles than with the 360° or Tesla configurations and thus transmits less information. In fact, the sensor configuration can have an important impact on the channel load. Table 6 shows that the 360° and Tesla sensor configurations can increase the CBR by around 40% compared with the forward sensor configuration. Thanks to the lower channel load generated, the forward sensor configuration is able to provide higher cooperative perception ratios than the 360°

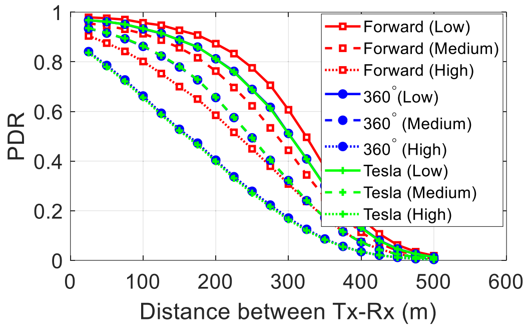

FIGURE 5. PDR (Packet Delivery Ratio) under different traffic densities (low, medium and high) and sensor configurations.

TABLE 6. Average CBR (Channel Busy Ratio).

Traffic density	Sensor configuration		
	Forward	360°	Tesla
Low	19.2%	27.6%	27.6%
Medium	31.8%	44.4%	44.4%
High	52.4%	71.3%	71.6%

and Tesla sensor configurations for the high traffic density scenario (Figure 4c).

Figure 4 has been obtained considering 100% penetration rate of cooperative perception, i.e. all vehicles in the scenario are CAVs and transmit CPMs. The effectiveness of cooperative perception depends on the number of vehicles that detect objects and share their information. Figure 6 shows the impact of the MPR (Market Penetration Rate) of cooperative perception. The figure shows that the object perception ratio increases with the MPR for low and medium traffic densities. However, when the traffic density is high, the perception ratio decreases for MPRs above 40% (Figure 6c). This degradation is again due to the significant increase of channel load at high traffic densities and the consequent increase in packet loses due to collisions. Figure 6 also shows that the sensor configuration does have an important effect on the perception when the MPR is low. In particular, the 360° and Tesla sensor configurations achieve significantly higher perception ratios than the forward sensor configuration, especially for low MPR. This is the case because cooperative perception cannot compensate well the perception limitations of the forward sensor configuration when there are few vehicles and not all vehicles can detect objects and share their information. However, all the sensor configurations provide similar perception ratios for MPR above 80%.

Figure 6 has shown that the sensors configuration has a strong impact on the perception that can be achieved with cooperative perception when the market penetration is low. The sensor configuration also has a high impact on the channel load generated. In fact, the sensor configuration has a strong impact on the amount of information shared with cooperative perception. This is the case because the sensor configuration affects the number of objects detected by each vehicle.

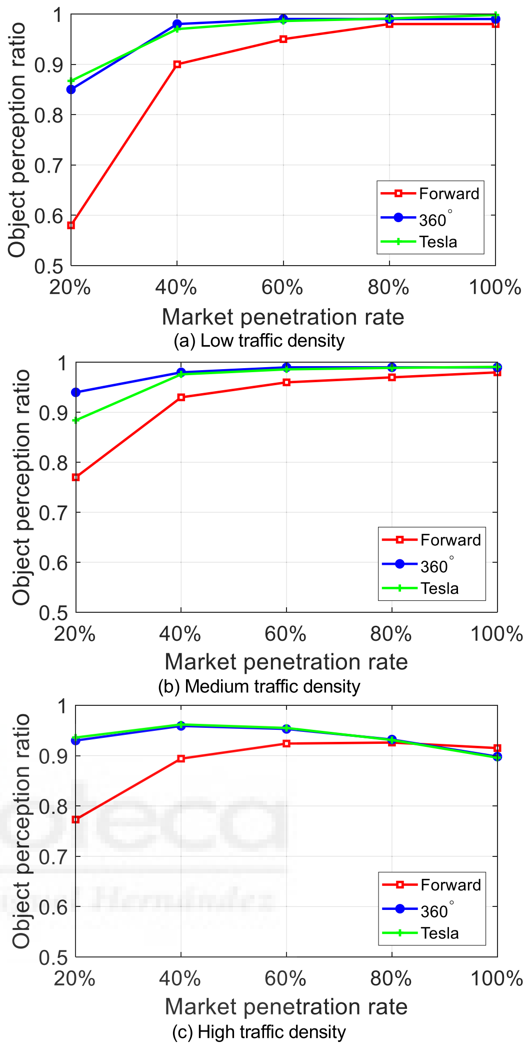

FIGURE 6. Object perception ratio under different traffic densities for different market penetration rates and for distances up to 350m.

As a consequence, the sensor configuration influences the amount of information transmitted by each vehicle. This changes the number of updates about the same object received by a vehicle under the observation time window. This number is referred to as detected object redundancy, and is depicted in Figure 7 as a function of the distance between the object and the vehicle receiving the CPM. Figure 7 corresponds to a 100% MPR.[7] The figure shows that the 360° and Tesla sensor configurations generate a significantly higher amount of redundancy compared to the forward sensor configuration. Despite the trends observed in Figure 7, all sensor configurations provide a similar object perception ratio up to around 300m for low and medium densities and up to around 200m for the high density (see Figure 4). This means that the higher redundancy and number of objects detected by the 360° and Tesla sensor configurations do not improve the perception

[7]Different redundancy values are observed with lower MPRs. However, the trend is maintained, i.e. sensors with wider FoV and larger ranges are characterized by higher redundancy levels.

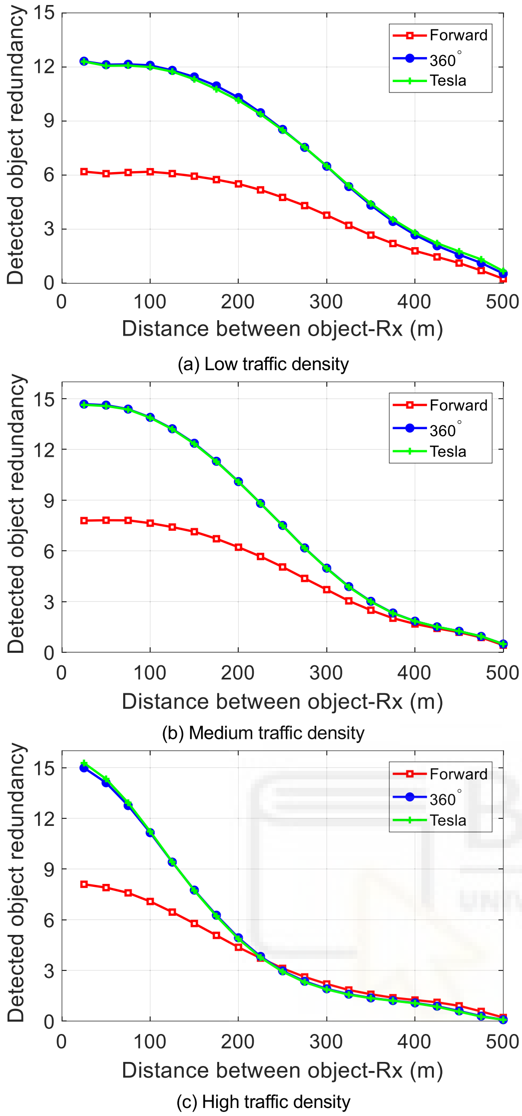

FIGURE 7. Detected object redundancy as a function of the distance between the detected object and the vehicle receiving the CPM under different traffic densities.

achieved with cooperative perception. Instead, they significantly increase the channel load as shown in Table 6.

Figure 7 also shows an interesting effect produced by the increase of the traffic density. When the traffic density increases, more vehicles transmit information about the same detected object and thus higher redundancy levels would be expected. However, such increase of the object redundancy is only produced at short distances. At medium and long distances, the degradation of the PDR (Figure 5) due to packet collisions reduces the detected object redundancy for medium and high traffic densities.

The previous results have been obtained considering that vehicles implement sensor fusion. In this case, if several sensors detect the same object, their information is fused and the object is reported only once in each CPM. If sensor fusion is not used, an object detected by multiple sensors is reported

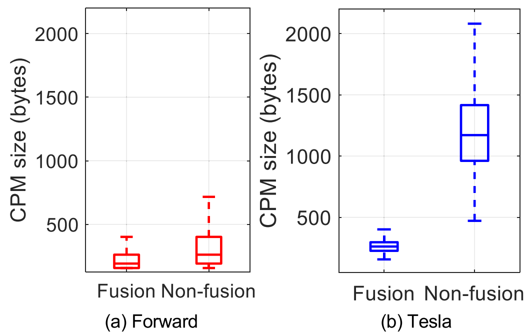

FIGURE 8. CPM size for medium traffic density and the forward and Tesla sensor configurations. Similar trends have been observed with low and high traffic densities for both sensor configurations.

multiple times in each CPM. This increases the message size as shown in Figure 8. This figure compares the CPM size with and without sensor fusion for the low traffic density scenario and the forward and Tesla sensor configurations. The results are presented as a box plot with the bottom and top edges indicating the 25th and 75th percentiles and the mark in the middle representing the median. Vertical lines show the most extreme data points that are not considered outliers. The results obtained show that the CPM size significantly increases when sensor fusion is not used, especially for the Tesla sensor configuration since it has more on-board sensors. In fact, the generated payload sizes of the Tesla non-fusion configuration exceed the maximum payload size [39]. In this case, the CPMs would have to be segmented and this could increase the risk of delaying the reception of the information about certain detected objects. Another main concern related with the increasing message size is that it significantly augments the channel load and the interference, and degrades the PDR (Figure 9) without providing additional relevant information to the receiving vehicles. Reducing the PDR degrades the effectiveness of cooperative perception since it reduces the probability to correctly receive CPM messages. This is actually visible in Figure 10 that depicts the object perception ratio when using sensor fusion and when not using

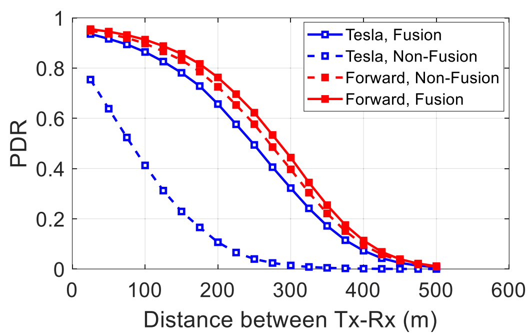

FIGURE 9. PDR (Packet Delivery Ratio) for medium traffic density and the forward and Tesla sensor configurations. Similar trends have been observed with low and high traffic densities for both sensor configurations.

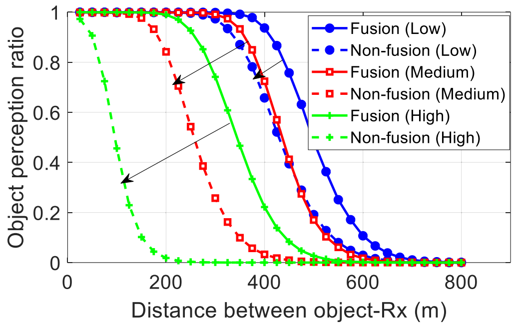

FIGURE 10. Object perception ratio as a function of the distance between the detected object and the vehicle receiving the CPM under different traffic densities (low, medium and high). These results correspond to the Tesla sensor configuration.

it. The figure clearly shows how the object perception ratio degrades when sensor fusion is not applied. The degradation is particularly relevant when the traffic density increases. The perception degradation observed in Figure 10 when not using sensor fusion is exclusively due to the degradation of the PDR (i.e. the V2X communication performance) since each vehicle can detect exactly the same number of objects when implementing sensor fusion and when not implementing it.

VII. IMPACT OF CONGESTION CONTROL ON COOPERATIVE PERCEPTION

The previous results have been obtained disabling the DCC mechanisms for congestion control. This was done to focus first on the impact of the sensors and market penetration rate on the perception and effectiveness of cooperative perception. The previous analysis has shown that cooperative perception can increase the channel load quite significantly under certain scenarios and configurations. Increasing the channel load can degrade the PDR, and ultimately the performance of V2X communications and the network scalability. To prevent this, an increase of the channel load above certain threshold activates the DCC mechanisms for congestion control. DCC can alter the performance and operation of collective perception. This can occur for example if the DCC queues CPM messages. Queuing would increase the information age and alter the regular reception of object updates. The DCC could also drop CPMs when the CPM generation rate is higher than the maximum transmission rate allowed by DCC Access. This could also significantly impact the effectiveness of cooperative perception. It is also important highlighting that CPM messages might have to coexist with other messages in the same channel. This increases the risk that DCC is activated and impacts the operation and effectiveness of cooperative perception. In this context, this section analyses the impact of DCC on cooperative perception. We focus first on the impact of DCC at the Access layer and then DCC at the Facilities layer. These are the two DCC components that mostly affect the transmission of CPM messages.

The scenario considered in this section is the high traffic density scenario described in section V, with 240 veh/km, a 100% MPR of cooperative perception and the 360° sensor configuration. We also assume that all vehicles transmit CAMs and CPMs in the same channel. This scenario is chosen to make sure DCC is activated and we can then study its impact on cooperative perception.

A. DCC ACCESS

In the considered scenario, the CBR experienced is equal to 75% when DCC Access is not applied. The use of DCC Access can significantly reduce the CBR as shown in Table 7. These results show that the Reactive approach reduces more aggressively the channel load and maintains the CBR around 37%. The Adaptive approach is designed to converge to the target CBR of 68% and this results in higher CBR levels. Table 7 also shows that nearly the same CBR is achieved independently of the DCC profiles of the messages.

TABLE 7. Average CBR (Channel Busy Ratio) with DCC Access for the high traffic density scenario.

DCC profile	DCC Access	
	Reactive	Adaptive
Different (CAM=DP2 and CPM=DP3)	36.9%	62.1%
Same (CAM=CPM=DP2)	37.8%	61.9%

One interesting effect that cannot be observed in Table 7 is the message transmission rate that DCC Access tolerates. When DCC is not applied, the average rates at which CAMs and CPMs are generated and transmitted are 3.3 Hz and 9.6 Hz, respectively. When DCC Access is enabled, the message transmission rates are reduced due to message dropping as shown in Table 8. Table 8 shows that the transmission rates of CAMs and CPMs are lower than the generation rates when both messages have the same DCC profile. When they have different DCC profiles, only CPMs are dropped because CAMs have higher priority.[8] Table 8 also shows that the Reactive and Adaptive approaches present nearly the same message transmission rate despite experiencing a very different CBR as shown in Table 7. This is the case because with the Reactive approach vehicles tend to synchronize with each other. This synchronization results in that vehicles change their state (and thus their T_{off}) nearly at the same time.

[8]This is the case because CAMs are prioritized since they are the basic awareness messages for active traffic safety applications.

TABLE 8. Average CAM and CPM transmission rates with DCC Access.

DCC profile	CAM		CPM	
	Reactive	Adaptive	Reactive	Adaptive
Different (CAM=DP2 and CPM=DP3)	3.3 Hz	3.3 Hz	3.9 Hz	4.0 Hz
Same (CAM=CPM=DP2)	2.7 Hz	2.1 Hz	5.6 Hz	6.0 Hz

A change to a more relaxed state, immediately allows the transmission of messages that were waiting in their queues. As a result, vehicles transmit nearly at the same time [48], which provokes that the Reactive approach generates a significant amount of packet collisions. Packet collisions reduce the channel load (and CBR) because when packets collide they overlap in time.

DCC Access can reduce the CBR and improve the PDR at the radio level, i.e. the ratio between the received and transmitted packets. This is particularly the case with the Adaptive approach as shown in Figure 11. This figure represents the PDR at the radio level when CAMs and CPMs are configured with the same DCC profile. The figure also shows that the Reactive approach actually degrades the PDR at the radio level despite reducing the CBR. This is due to the high probability of packet collisions for the Reactive approach due to the synchronization problem previously explained. Similar results are obtained when analyzing the PDR at the radio level when CAMs and CPMs have different DCC profiles.

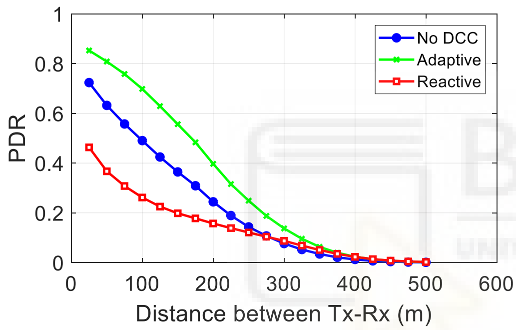

FIGURE 11. PDR (Packet Delivery Ratio) at the radio level as a function of the distance between transmitter and receiver without and with DCC Access when CAMs and CPMs have the same DCC profile.

To better understand the effect of DCC Access on the performance of collective perception, Figure 12 plots the PDR for CPMs at the radio and application levels for Reactive and Adaptive approaches. At the application level, the PDR is defined as the ratio between the received and generated CPMs. Thus, a CPM generated at the Facilities layer but dropped by DCC Access is considered as a packet lost when computing the PDR at the application level.[9] Figure 12 shows that DCC Access degrades the performance at the application level due to packet dropping. This degradation is observed for both Reactive and Adaptive approaches. However, the Reactive approach shows a significantly lower PDR at the application level than the Adaptive one due to its lower PDR at the radio level. The figure also shows that this degradation produced at the application level due to packet dropping is particularly relevant when CAMs and CPMs have different DCC profiles. In this case, CPMs are the only messages dropped by DCC since they have lower priority than CAMs.

[9]This packet loss would not be counted in the PDR at the radio level since the packet was never transmitted.

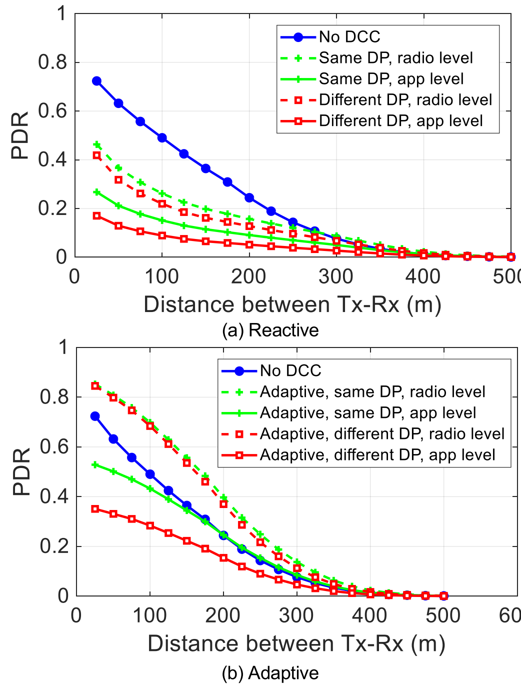

FIGURE 12. PDR (Packet Delivery Ratio) for CPMs at the radio and application levels as a function of the distance between transmitter and receiver without DCC and with DCC Access when CAMs and CPMs have the same or different DCC profile.

The PDR at the radio and application levels affect the object perception ratio. However, the differences observed in the PDR of Figure 12 are not directly transferred to Figure 13. Figure 13 depicts the object perception ratio as a function of the distance between the object and the vehicle receiving the CPM. Figure 13a shows that the object perception ratio significantly degrades with the Reactive approach following the trend observed in Figure 12a where Reactive significantly degrades the PDR at the application level. This once again clearly proves that the Reactive approach degrades the performance of cooperative perception despite reducing the channel load. Figure 13b shows the perception achieved with the Adaptive approach. For distances below 200m, the higher PDR achieved at the application level without DCC does not result in a significant improvement of the object perception ratio. This is the case because the object perception ratio is already close to 1 at distances below 200m when DCC is applied. Therefore, without DCC the perception ratio cannot be significantly improved despite its higher PDR at distances below 200m. However, DCC Adaptive improves the object perception ratio for distances beyond 200m when CAMs and CPMs have the same DCC profile. A higher perception is achieved despite having nearly the same PDR at the application level than when DCC is not used. This effect is produced due to the different nature of packet errors with and without DCC. When DCC is not applied, more packet collisions are produced due to the higher channel load. When two (or more) packets collide, more than one packet can be lost due to such collision. Therefore, when

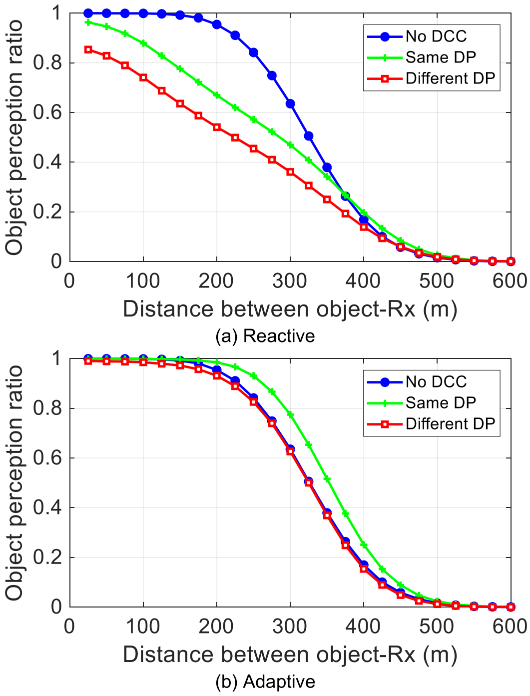

FIGURE 13. Object perception ratio as a function of the distance between the detected object and the vehicle receiving the CPM without DCC and with DCC Access.

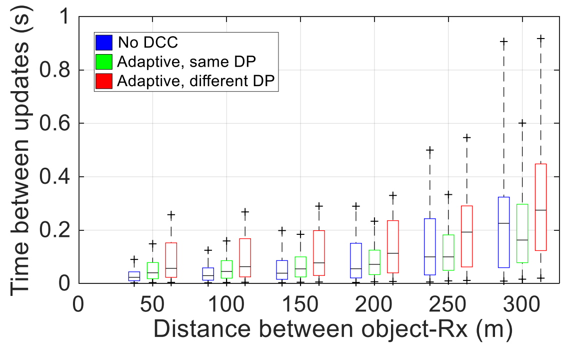

FIGURE 14. Time between object updates as a function of the distance between the detected object and the vehicle receiving the CPM.

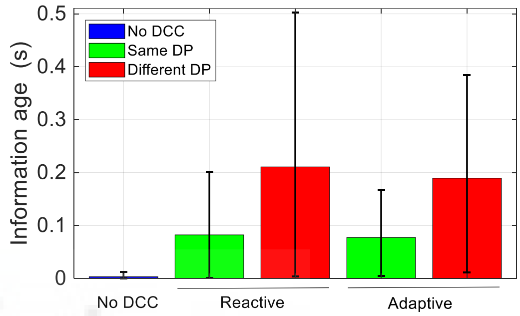

FIGURE 15. Average information age for CPMs received with and without DCC Access. The bars represent the average values and the vertical lines represent the 5th and 95th percentiles.

DCC is not applied, consecutive packet loses are produced with higher probability. This effect is not produced with the packets dropped by DCC, since one packet drop does not affect the reception of other packets. Consequently, packet collisions can increase the time between consecutive object updates. This effect can be observed in Figure 14 that plots the time between object updates as a function of the distance between the detected object and the vehicle receiving the CPM in bins of 50 m. The time between updates shown in Figure 14 corresponds to that measured with the Adaptive approach.[10] Results are presented using box plots with the bottom and top of each box representing the 25th and 75th percentiles. The median is represented inside each box with the black horizontal line. The vertical lines plotted above and below each box represent the 5th and 95th percentiles. Results in Figure 14 reveal that there is higher variability in the time between consecutive updates when DCC is not applied due to the higher probability of consecutive packet loses due to collisions. For example, the 95th percentile of the time between updates is around 0.9 s at 300 m without DCC, and around 0.6 s with DCC when CAM and CPM have the same profile. However, the variability also increases with DCC when CAM and CPM have different profiles for distances higher than 200 m since CPMs have lower priority than CAMs.

The previous results show that DCC Access has an impact on the probability of receiving information about an object through CPMs and therefore on the object perception ratio. However, they do not quantify if the information received is outdated. This is important because connected automated driving requires updated data and low transmission latencies. However, queuing at DCC Access can significantly delay the transmission of messages. To analyze the impact of DCC Access on the freshness of the received information, we measure the information age that is defined as the difference between the time the CPM is generated and the time the CPM has been received. Figure 15 represents the information age obtained without DCC and with DCC (Reactive and Adaptive) when CAMs and CPMs are configured with the same and different DCC profiles. The bars represent the mean values and the vertical lines correspond to the 5th and 95th percentiles. The distance between the transmitter and receiver does not have a significant impact because the propagation delay is negligible. The results obtained show that DCC significantly increases the information age when compared with the scenario without DCC. When DCC is not used, all the generated CPMs are immediately transmitted. However, with DCC, the generated CPMs must often wait in the queue before transmission. This waiting time causes the received information to be outdated by up to 0.4s (Adaptive) or 0.5s (Reactive) when CAM and CPM have different DCC profiles. This provokes a tracking error of up to around 5 m when CAM and CPM have different DCC profiles. This

[10] Similar trends are obtained with the Reactive approach, but with higher times between updates (approximately 2x increase).

is a non-negligible error that can degrade the effectiveness of cooperative perception when implementing DCC. This is despite the possibility to achieve a higher object perception ratio (Figure 13) since detecting more objects is not useful if the information about the detected objects is outdated or not sufficiently fresh.

B. DCC FACILITIES

DCC Facilities is optional as defined in the current Technical Specification draft. However, it can help mitigate the increase of the information age caused by DCC Access and improve the perception capabilities as we demonstrate in this section. DCC Facilities is being designed so that messages are generated at the Facilities layer at the maximum rate tolerated by DCC Access. This is done to reduce the queuing time at the Access layer and limit packet drops. To this aim, DCC Facilities distributes the resources among the different services that generate messages with the same DCC profile. We have therefore considered in this section that both CAMs and CPMs have the same DCC profile, DP2.

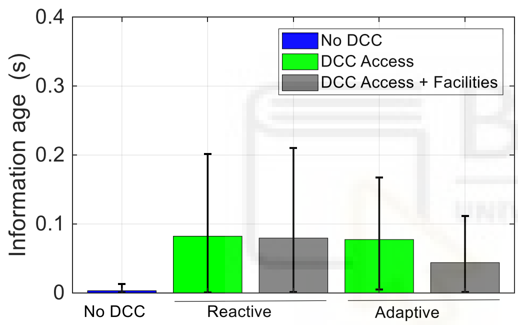

FIGURE 16. Average information age for CPMs received when CAMs and CPMs have the same DCC profile. The bars represent the average values and the vertical lines represent the 5th and 95th percentiles.

Figure 16 compares the information age obtained without DCC, with DCC Access only and with the combination of DCC Access and DCC Facilities. The bars represent the mean value and the vertical lines show the 5th and 95th percentiles. As it can be observed, DCC Access significantly increases the information age as we previously showed. However, the combination of DCC Access and DCC Facilities significantly reduces the information age, especially when considering the Adaptive approach. This improvement is achieved because DCC Facilities controls the generation following the limits provided by DCC Access so that messages are not generated if they are going to be queued. The reduction of the information age when DCC Access and DCC Facilities are combined decreases the tracking error below 1.5 m with the Adaptive approach. This error was under 2.3 m with DCC Access (Adaptive) when CAM and CPM have the same profile and below 0.17 m when DCC is not used. The information age is not improved when the Reactive approach is used. This is the case because the channel load variations do not allow DCC Facilities to accurately track the packet transmission rate allowed by the Reactive approach (Table 1) and hence to reduce the queuing time.

DCC Facilities controls the generation of CPMs based on the possibility to transmit them at the DCC Access. This significantly reduces the percentage of CPMs dropped. The percentage of CPMs dropped with DCC Access only is 41.6% for Reactive and 37.5% for Adaptive. The combination of DCC Access and DCC Facilities reduces the CPMs dropped to 12.8% for Reactive and 8.7% for Adaptive. This effect is produced because DCC Facilities reduces the packet generation rate at the Facilities layer following the limits provided by DCC Access. This reduction is shown in Figure 17 that shows the PDF of the number of CPMs generated at the Facilities layer per second per vehicle. The figure also shows that DCC Access generates the same number of CPMs than the scenario without DCC (irrespective of whether using the Reactive or Adaptive approach). This is the case because DCC Access controls messages at the access layer and does not modify the way CPMs are generated at the Facilities layer. When DCC Access is combined with DCC Facilities, the number of CPMs generated per second is reduced. As a consequence, each CPM includes information about a larger number of detected objects. This is the case because the time interval between CPM generations is longer, and thus more objects satisfy the conditions to be included in a CPM since the last time a CPM was generated. This increase of the number of objects in each CPM with DCC Facilities can be observed in Figure 18. Despite the variation observed in the number of CPMs generated per second and the number of objects contained in each CPM, DCC Facilities is designed to generate the load admitted by DCC Access, but not more. The obtained results demonstrate that this goal is achieved with the Adaptive approach. This is the case because the combination of DCC Access and DCC Facilities is able to maintain the CBR around 61.9% when the Adaptive approach is considered. It is the same CBR than the one achieved in the scenario where only DCC Access is used (Table 7). However, the percentage of packet drops is significantly lower when DCC Facilities is used (7.5%) than when it is not used (37.2%).

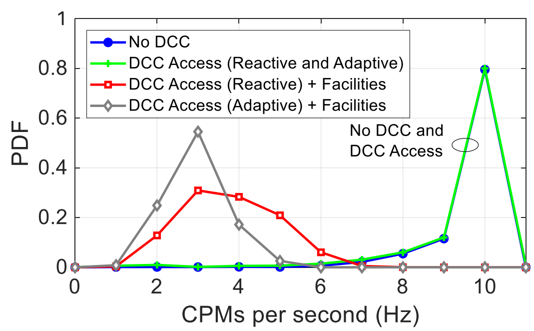

FIGURE 17. PDF of the number of CPMs generated at the Facilities layer per second per vehicle when CAMs and CPMs have the same DCC profile. When DCC Access is used alone, the same results are obtained for Reactive and Adaptive approaches since DCC Access does not modify the generation of CPMs.

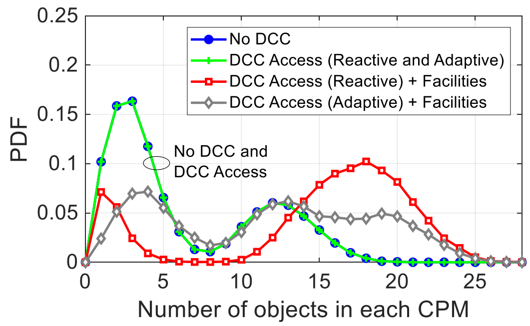

FIGURE 18. PDF of the number of objects included in each CPM when CAMs and CPMs have the same DCC profile. When DCC Access is used alone, the same results are obtained for Reactive and Adaptive approaches.

The use of DCC Facilities with the Reactive approach has a different effect on the CBR. It increases the CBR to 46.7% compared to the scenario when only DCC Access is used (37.8%). This increase is produced because DCC Facilities mitigates the synchronization problem that characterizes the Reactive approach and that has been previously explained. DCC Facilities mitigates the synchronization problem because it allows each vehicle to generate (and transmit) messages with different time intervals based on their past generated messages. Mitigating the synchronization problem increases the CBR because there are less packet collisions and thus packets do not overlap in time. Consequently, the implementation of DCC Facilities significantly increases the PDR. This can be observed in Figure 19a for Reactive and in Figure 19b for Adaptive. The PDR at the radio level is especially improved with the Reactive approach due to

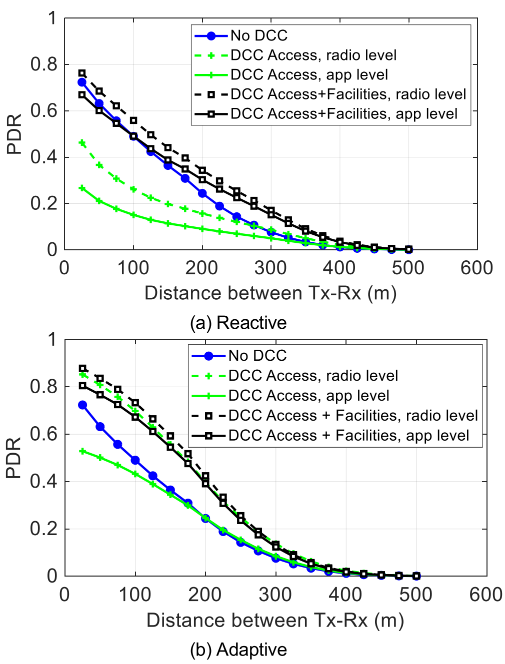

FIGURE 19. PDR (Packet Delivery Ratio) for CPMs at the radio and application levels as a function of the distance between transmitter and receiver when CAMs and CPMs have the same DCC profile.

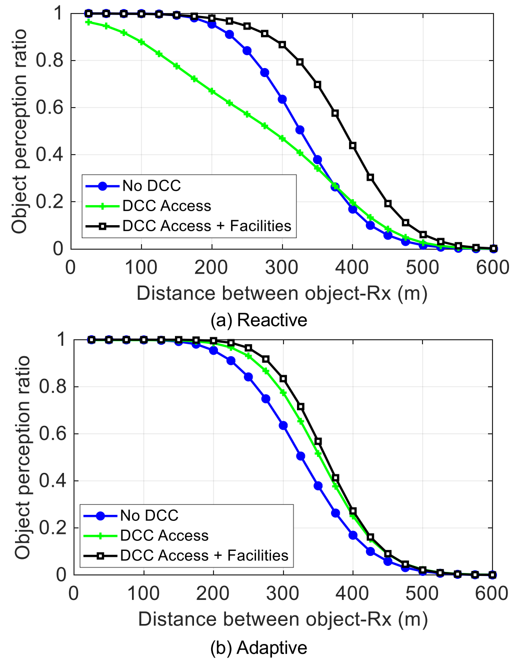

FIGURE 20. Object perception ratio as a function of the distance between the detected object and the vehicle receiving the CPMs when CAMs and CPMs have the same DCC profile.

the mitigation of the synchronization problem. It is nearly maintained for Adaptive since the same CBR is achieved. The PDR at the application level is significantly improved for both Reactive and Adaptive. This is due to the low number of packets dropped by DCC when DCC Access and DCC Facilities are combined. Thanks to the improvement of the PDR, the combination of DCC Access and DCC Facilities improves the object perception ratio. This is visible in Figure 20 that compares the object perception ratio when not using DCC, when using DCC Access only and when combining DCC Access and DCC Facilities. Figure 20 reports the object perception ratio for the Reactive and Adaptive approaches. The improvement produced by DCC Facilities is particularly relevant for the Reactive approach given the high PDR increase. In fact, the Reactive approach slightly outperforms the Adaptive one for distances beyond 300m. This improvement is produced due to the higher PDR at the application level of the Reactive approach at such distances (Figure 19) due to its lower CBR and thus lower packet collisions. All these results clearly show that the combination of congestion control functions at the Access and Facilities layers can significantly improve cooperative perception. This is the case because it augments the object perception ratio, reduces the information age, and improves the PDR compared with the scenario with DCC Access only.

VIII. CONCLUSION

This paper analyzes in detail the effectiveness and operation of cooperative perception in connected automated driving. The study shows that cooperative perception significantly improves the perception compared to scenarios in which vehicles exclusively rely on their on-board sensors. The effectiveness of cooperative perception is analyzed for different sensor configurations and market penetration rates. The study shows that very high perception levels can be achieved with penetration rates of only 40%. The perception achieved with cooperative perception strongly depends on the sensors' field of view and range when the market penetration rate is low. However, the impact of the sensors' characteristics on the performance of cooperative perception decreases with the market penetration rate.

Cooperative perception can increase the channel load in the network, which has the risk to reduce the V2X communication performance and degrade the network's scalability. V2X networks control the channel load using congestion control protocols. This study has then also analyzed the impact of congestion control on cooperative perception. To this aim, the study has focused on the DCC algorithm and has evaluated the impact of congestion control functions at the access and facilities layers. At the access level, the study compares for the first time the performance achieved with the Reactive and Adaptive solutions for cooperative perception. The study demonstrates that the Adaptive approach significantly improves the perception achieved but can increase the information age (or freshness) of the exchanged messages compared to scenarios where DCC is not used. This reduces the value of cooperative perception since latency is critical in connected automated driving. This study demonstrates then for the first time that this challenge can be partially addressed through the combination of DCC Access and DCC Facilities. We demonstrate that the combination of DCC Access and DCC Facilities increases the perception and reduces the information age when compared with the DCC Access configuration. This is achieved by dynamically adapting the rate at which messages are generated. This reduces the probability to drop cooperative perception messages (and hence information about the detected objects) and the channel load, which ultimately benefits the V2X network and the effectiveness of cooperative perception. This study therefore demonstrates how critical is the configuration of DCC Access and the importance of DCC Facilities for the development of CAVs. This is particularly relevant for DCC Facilities since it is still a draft that is considered optional and that has not yet been adopted by industry organizations like the C2C-CC. The outcome of this study can provide them valuable knowledge towards an efficient and effective V2X configuration and deployment.

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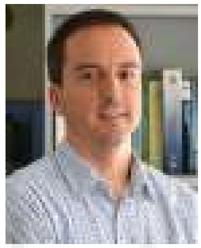

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Annex A.3 Publication

Redundancy Mitigation in Cooperative Perception for Connected and Automated Vehicles

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Abstract— **Cooperative perception (or cooperative sensing or collective perception) enables connected and automated vehicles to exchange sensor data in order to improve their perception of the driving environment. ETSI is currently developing a standard for collective perception. The standard defines the message format and generation rules. These rules identify when a message should be transmitted and what information it should include. This study shows first that the current ETSI solution generates many redundant collective perception messages that increase the channel load and can compromise the networks' scalability. Unnecessary redundancy can reduce the reliability of V2X (Vehicle to Everything) communications and ultimately decrease the effectiveness of collective perception. This study proposes a modification of the current ETSI solution to control redundancy and avoid the transmission of unnecessary CPM data or messages. The evaluation shows that our proposal significantly reduces the redundancy and channel load and improves the reliability of V2X communications compared to current ETSI solution for collective perception. This is achieved while maintaining the perception achieved by ETSI for the safety-critical short and medium distances.**

Index Terms— Collective perception, cooperative perception, cooperative sensing, redundancy, message generation, connected automated vehicles, V2X, vehicular networks, ITS-G5, ETSI.

I. INTRODUCTION

Autonomous vehicles use onboard sensors to perceive the environment. The sensors´ perception capabilities are reduced under the presence of obstacles (including other vehicles) or adverse weather conditions. Vehicles can improve their perception using wireless communications to exchange sensor data with nearby vehicles and infrastructure. This is known as cooperative perception, collective perception or cooperative sensing. Previous studies have demonstrated that collective perception or cooperative sensing can improve the perception capabilities of vehicles even beyond their sensors' detection range [1]. The study in [1] analyzes the advantages and disadvantages of exchanging raw sensor data, processed metadata or compressed data. Exchanging raw sensor data would require significantly large bandwidths that cannot be provided by existing V2X (Vehicle to Everything) technologies such as DSRC, ITS-G5 or C-V2X. Recent studies (e.g. [2] and [3]) hence focused on the exchange of basic information about detected objects (e.g. their position, speed and size) to reduce the communication bandwidth required for collective perception. This approach has been adopted in Europe where ETSI (European Telecommunications Standards Institute) is currently defining the standard for the Collective Perception Service (CPS) [4]. The CPS draft standard defines the Collective Perception Message (CPM) format and the CPM generation rules. These rules establish when vehicles should generate a new CPM message and the information it should include. A CPM includes one common header and multiple containers with information about the vehicle that generates the CPM, the capabilities of its onboard sensors, and the detected objects (their position, speed, size, etc.). The authors analyzed in [5] the current CPS draft standard and demonstrated that current ETSI CPM generation rules result in the frequent transmission of CPMs that include information about a small number of detected objects. This can compromise the network's scalability since most of the transmitted data is headers rather than data about detected objects. The analysis also showed that current CPM generation rules result in significant redundancy. For example, the study showed that vehicles can receive as much as 25 to 50 times per second the same data about a detected object under the evaluated scenarios. This is the case because current CPM generation rules are exclusively based on changes of the detected objects' dynamics (position and speed). In this case, all vehicles in the vicinity of a detected object that detect a change in the objects' dynamics will generate a CPM with the same information about the detected object. Redundancy can be positive to confirm the accurate detection of objects or vehicles. However, an excessive redundancy can overload the V2X communications channel and compromise the network's scalability. It can also negatively impact the perception accuracy if an overloaded channel results in packet collisions. These collisions can reduce the probability of receiving CPM messages and ultimately impact the effectiveness of collective perception or cooperative sensing.

This paper proposes a modification of the current ETSI CPS solution in order to control the redundancy in the network without degrading the perception capabilities of Connected and Automated Vehicles (CAVs). The proposal controls redundancy by preventing vehicles to report about detected objects in CPMs if they have already received updates about

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the same object from other vehicles. Transmitting another CPM with the same detected object data will increase redundancy without a significant benefit to neighbor vehicles that have already received the same data from other vehicles. This proposal is aligned with the vision outlined in [6] where authors discuss the need to consider the value of the information about a detected object to decide whether it should be transmitted or not. This paper demonstrates that the proposed solution reduces significantly the redundancy in the network as well as the channel load and improves the V2X reliability. In addition, our proposal maintains the perception achieved with the current ETSI solution for short and medium distances (up to around 200m radius). These distances are critical for the safety of CAVs.

II. Collective Perception Standardization

Current ETSI developments to specify the CPS service are described in the Technical Report in [4] and will serve as baseline for the specification of CPS in ETSI TS 103 324. The Technical Report describes the CPM format and the CPM generation rules. CPM messages include an ITS (Intelligent Transport Systems) PDU (Protocol Data Unit) header and 4 types of containers: Management Container, Station Data Container, Sensor Information Containers (SICs) and Perceived Object Containers (POCs). The ITS PDU header includes Data Elements like the protocol version, the message ID and the Station ID. The Management Container is mandatory and provides basic information about the transmitting vehicle (e.g. its position). The position information is used by the receiver to reference the detected objects. The Station Data Container is optional and includes additional information about the transmitting vehicle (e.g. its speed, heading, or acceleration). In addition, the CPM can include up to ten SICs to describe the capabilities of the sensors embedded in the transmitting vehicle. Finally, the POCs provide information about the detected objects (e.g. the distance between the detected object and the transmitting vehicle), the speed and dimensions of the object, and the time at which these measurements were done. A single CPM can include up to 255 POCs.

The CPM generation rules define when a vehicle should generate and transmit a CPM and the information to be included in the CPM. Current ETSI CPM generation rules [4] establish that a vehicle has to check every *T_GenCpm* if a new CPM should be generated and transmitted. By default, *T_GenCpm* is set equal to 100ms although it can be equal to any multiple of 100ms in the range between 100ms and 1000ms. For every *T_GenCpm,* a vehicle should generate a new CPM if it has detected a new object, or if any of the following conditions are satisfied for any of the previously detected objects:

1. Its absolute position has changed by more than 4m since the last time its data was included in a CPM.
2. Its absolute speed has changed by more than 0.5m/s since the last time its data was included in a CPM.
3. The last time the detected object was included in a CPM was 1 (or more) seconds ago.

A vehicle includes in a new CPM all new detected objects and those objects that satisfy at least one of the previous conditions. The vehicle still generates a CPM every second even if none of the detected objects satisfy any of the previous conditions. The information about the onboard sensors is included in the CPM only once per second.

III. Motivation

This section evaluates the current ETSI CPS solution to motivate our proposal. In particular, the section evaluates the level of redundancy generated by the current ETSI CPS proposal. To this aim, we consider a 5km long six-lane (three per direction) highway scenario[1] that we simulate using the road mobility simulator SUMO following the conditions reported in Table I. We consider two traffic densities following the V2X simulation guidelines in [7]. The speed of vehicles at each lane is configured using statistics from the PeMS database for a typical 3-lane US highway [8].

Table I. Scenario

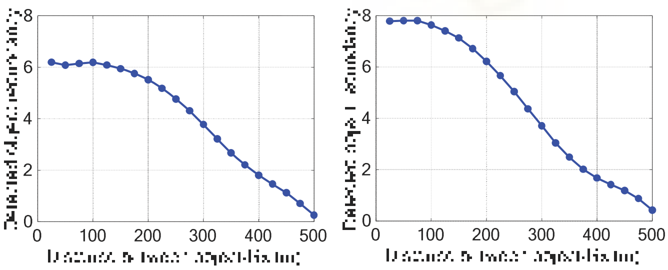
Traffic density	60 veh/km	120 veh/km
Speed per lane	140 km/h	70 km/h
	132 km/h	66 km/h
	118 km/h	59 km/h

V2X communications are simulated using the network simulator ns3 [9]. In our analysis, all vehicles communicate using ETSI's ITS-G5 standard (based on IEEE 802.11p) over the same channel. The propagation effects are modeled using the Winner+ B1 propagation model following [7]. The transmission power is set to 23dBm and the packet sensing threshold to -85dBm. All vehicles transmit using the 6Mbps data rate (i.e. they utilize QPSK modulation with ½ code rate). The ns3 simulator has been extended with a CPS component implemented by the authors. The component creates CPM messages based on the ETSI CPM message format [5]. CPM messages are generated following current ETSI´s solution (Section II) with *T_GenCpm*=0.1s. Vehicles are configured with two forward sensors following [4] and [5]. The first sensor has a 65m range and a FoV (Field of View) of ±40º. The second sensor has a 150m range and a ±5º FoV. The object detected by two sensors are assumed to be fused.

ETSI CPM generation rules include information about a vehicle in a CPM every 200ms and 300ms for the low and high traffic density scenarios respectively. For example, vehicles move at speeds between 32.7m/s and 38.8m/s in the low traffic density scenario. Vehicles then need 0.11s to 0.13s to move 4m. *T_GenCpm* is defined as a multiple of 100ms. Therefore, the information about a vehicle is included in a CPM every 200ms for low traffic densities. Similar calculations can be done for the high traffic density scenario. These calculations are important to select the adequate observation time window and correctly evaluate the performance and effectiveness of the collective perception service. We then consider observation time windows of 200ms and 300ms for the low and high traffic density scenarios, respectively. These values correspond to the time required by ETSI CPM generation rules for a vehicle to send an update about an object in a CPM for the two traffic densities.

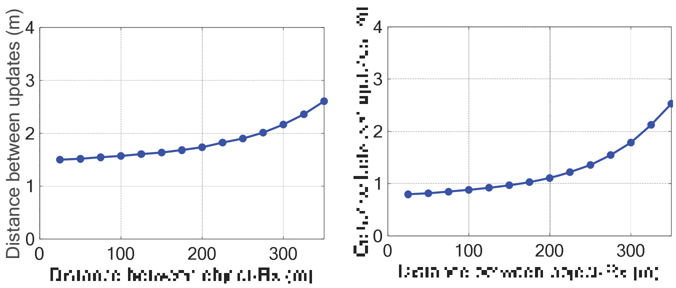
[1] Statistics are only collected for vehicles located in a 2km road segment around the middle of the scenario in order to avoid boundary effects.

Figure 1 plots the number of times a vehicle receives CPMs with data about the same object over the selected observation time windows. These CPMs come from different vehicles that detect the same object. The metric depicted in Figure 1 is referred to detected object redundancy. It is represented as a function of the distance between the detected object and the vehicle receiving the CPMs. Figure 1 highlights the redundancy levels resulting from current ETSI CPM generation rules. Rather than receiving a single object update per observation window, on average, vehicles receive more than 5 updates for low and more than 6 updates for high traffic densities respectively up to distances of around 200m. This results that the vehicles receive updates about objects more frequently than really necessary. This is illustrated in Figure 2 that plots the distance travelled by an object between two successive CPMs that include information about that object. Results are again plotted as a function of the distance between the object and the vehicle receiving the CPMs. This figure clearly shows that a vehicle receives updates about a detected object much more frequently than in fact intended by ETSI CPM generation rules. Figure 2 shows that on average a vehicle will receive an object update less than every 1.7m for low density and less than every 1.1m for high density up to distances of around 200m. This is in contrast to the 4m threshold established by the CPM generation rules to decide when an update should be transmitted. Sending frequent updates might be unnecessary from the perception point of view and can significantly increase the load on the communications channel. This can augment packet collisions and reduce the reliability of V2X communications which can ultimately decrease the perception capabilities of CAVs. We propose in the following section a modification of the current ETSI CPS to control the unnecessary detected object redundancy while minimizing the changes to the standards.



(a) Low density (b) High density

Figure 1. Object redundancy as a function of the distance between the detected object and the vehicle receiving the CPMs.



(a) Low density (b) High density

Figure 2. Average distance travelled by a detected object between two successive CPMs reporting about this object. Metric represented as a function of the distance between the object and the vehicle receiving the CPMs.

IV. Proposal

The objective of our proposal is to reduce the redundancy in the transmission of CPMs without decreasing the perception capabilities of CAVs for short and medium distances since CPMs are critical for their safety. Our proposal is executed before the original ETSI CPM generation rules to filter out the detected objects that have been recently transmitted by a nearby vehicle. To this aim, the proposed algorithm analyses every *T_GenCpm* the change in the absolute position (ΔP_R) and speed (ΔS_R) of every detected object since the last time the object was received in a CPM from other vehicles. If $\Delta P_R \leq P_Threshold$m and $\Delta S \leq S_Threshold$m/s, the object will not be included in the CPM even if it complies with the original ETSI CPM generation rules' conditions, which are analyzed later. *P_Threshold* and *S_Threshold* threshold values must be equal or smaller than 4m and 0.5m/s respectively to reduce redundancy. The rationale for this proposal is that if a vehicle has recently received an update about the same object from other vehicles, there is no need for the vehicle to send another update about this object since neighbor vehicles will have already received the data from other vehicles. This reduces unnecessary redundancy. The pseudo-code of the proposed extension to the ETSI CPM generation rules is described in lines 1-5 of Algorithm I. Then, the algorithm follows the original ETSI CPM generation rules and computes for the remaining detected object the variation of absolute position (ΔP), the variation of speed (ΔS) and the time elapsed (ΔT) since the last time the detected object was included in a CPM. A new CPM is generated if at least one of the conditions specified in Section II is satisfied following the current ETSI CPM generation rules. If it is the case, the CPM should include the information about the detected objects that satisfy ΔP>4m or ΔS>0.5m/s or ΔT>1s and that were not omitted by our proposed redundancy reduction mechanism. The pseudo-code for this process is reported in lines 6-11 of Algorithm I.

Algorithm I.
Input: Detected Objects
Output: Objects (if any) to include in CPM
Execution: Every *T_GenCpm*

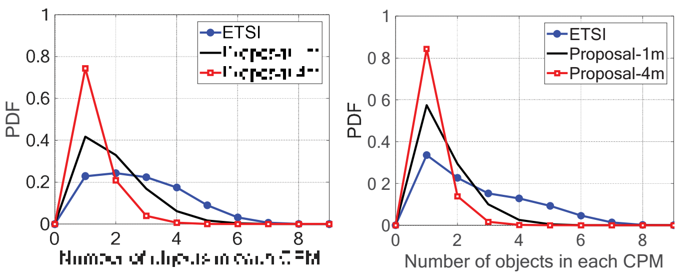
1. **For** every detected object **do**
2. Calculate ΔP_R and ΔS_R since last time received in a CPM
3. **If** $\Delta P\_R < P\_Threshold$ && $\Delta S\_R < S\_Threshold$ **then**
4. **Continue**
5. **Else**
6. Calculate ΔP, ΔS and ΔT since last time included in a CPM
7. **If** ΔP>4m || ΔS>0.5m/s || ΔT>1s **then**
8. Include object in current CPM
9. **End if**
10. **End If**
11. **End For**

V. Evaluation

Our proposal is analyzed using the simulation set-up and conditions described in Section III. The proposed algorithm is implemented considering two threshold configurations: (*P_Threshold*=1m, *S_Threshold*=0.5m/s) and (*P_Threshold*=4m, *S_Threshold*=0.5m/s). These configurations are referred to as proposal-1m and proposal-4m in this evaluation.

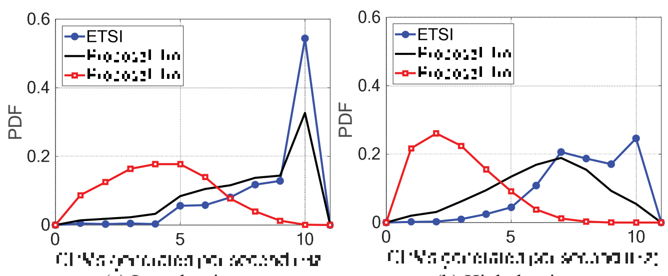
Figure 3 compares the PDF of the number of objects included in each CPM with the current ETSI generation rules and our proposal. Figure 3 shows that our proposal reduces the number of detected objects included per CPM under low and high traffic densities and for both configurations. The largest reductions are obtained with the proposal-4m configuration. Figure 3 also shows that our proposal reduces the number of objects included per CPM when augmenting the traffic density. This is because when the density increases there are many vehicles that transmit the same redundant data with the ETSI CPM generation rules. Our proposal reduces the redundancy and has then a higher impact when the traffic density increases. This is very interesting since higher densities can compromise the networks' scalability.

Our proposal also reduces the number of CPMs transmitted per second. This is visible in Figure 4 that compares the PDF of the number of CPMs generated per vehicle per second with the ETSI CPM generation rules and our proposal. The proposal-4m configuration achieves again the higher reduction levels. These results clearly show that our proposal generates less CPMs per second with smaller size than the current ETSI CPM generation rules. This reduces the channel load as illustrated in Table II. The channel load is estimated in terms of the average CBR (Channel Busy Ratio). The CBR is defined as the percentage of time that the channel is sensed as busy. Table II shows that our proposal significantly reduces the channel load as a consequence of the trends depicted in Figure 3 and Figure 4. In particular, the proposal-1m configuration reduces the CBR by 17%-26% and the proposal-4m configuration by 58%-68% when compared to the current ETSI solution. As expected, Table II shows that the CBR increases with the traffic density. However, lower increases are observed with our proposal following the trends observed in Figure 3 and Figure 4. This shows that the proposed algorithm can better cope with increases in the network load.



(a) Low density (b) High density

Figure 3. PDF of the number of objects included in each CPM.



(a) Low density (b) High density

Figure 4. PDF of the number of CPMs generated per second.

TABLE II. AVERAGE CBR (CHANNEL BUSY RATIO)

Policy	Traffic density	CBR
ETSI	Low	19.2 %
	High	31.8 %
Proposal-1m	Low	15.9 %
	High	23.4 %
Proposal-4m	Low	8.1 %
	High	10.1 %

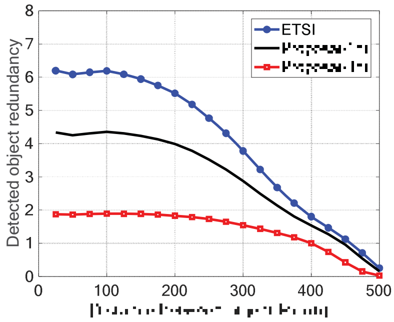
TABLE III. DISTANCE (METERS) WITH PDR ≥ 0.9

Policy	Traffic density	PDR
ETSI	Low	181m
	High	112m
Proposal-1m	Low	200m
	High	160m
Proposal-4m	Low	250m
	High	233m

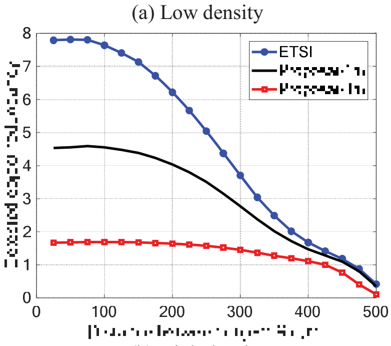
Reducing the CBR and channel load reduces the packet collisions and improves the PDR (Packet Delivery Ratio). This is actually shown in Table III that reports the distance up to which a PDR equal or higher than 0.9 is guaranteed[2]. Table III shows that our proposal increases this distance compared to the current ETSI solution. In particular, the proposal-1m configuration increases it by 10% and 42% in low and high traffic densities, and the proposal-4m configuration by 38% and 108% respectively. These results demonstrate that our proposal increases the reliability of V2X communications.

Figure 5 shows the effectiveness of our proposal to reduce the redundancy introduced by current ETSI's CPS solution. The figure depicts the object redundancy as a function of the distance between the object and the vehicle receiving the update or CPM. This metric represents the number of times a vehicle receives CPMs with an update about the same object over the observation time window. The object redundancy decreases with the distance due to the propagation effects that reduces the PDR. Figure 5 shows that our proposal effectively reduces the number of object updates compared to ETSI´s solution in order to control the channel load. This reduction is achieved without sacrificing the perception performance for short and medium distances that are critical for the safety of CAVs. This is illustrated in Figure 6 that compares the perception achieved with the current ETSI CPM generation rules and our proposal. The perception is estimated with the object perception ratio that is defined as the probability to detect an object (i.e. a vehicle in this study) within the observation time window. We consider that a vehicle successfully detects an object if it receives at least one CPM with information about that object during the observation time window. Figure 6 also shows the perception achieved with an autonomous vehicle that only uses its sensors and does not implement V2X communications. In this case, we consider that a vehicle successfully detects an object if the sensors detect the object during the same time window. Figure 6 plots the average object perception ratio as a function of the distance between the detected object and the vehicle receiving the CPMs. Figure 6 shows that relying exclusively on the onboard sensors results in a very low perception performance. The perception is significantly improved when using

[2] This distance is considered a V2X performance reference by some standardization organizations such as the 3GPP [7].

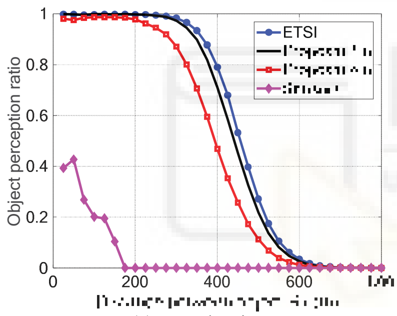


(a) Low density

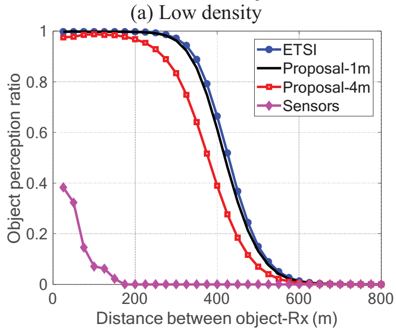


(b) High density

Figure 5. Detected object redundancy as a function of the distance between the detected object and the vehicle receiving the CPM.



(a) Low density



(b) High density

Figure 6. Object perception ratio as a function of the distance between the detected object and the vehicle receiving the CPMs

collective perception or cooperative sensing. Figure 6 shows that our proposal achieves the same (or nearly the same) perception as ETSI´s current solution for the critical short and medium distances (up to around 200m) and both traffic densities. In particular, the perception performance is identical for the proposal-1m configuration. These results show that the proposed algorithm can reduce the redundancy without degrading the perception capabilities compared to current ETSI´s solution at the critical short and medium distances. It should be noted that the performance is evaluated considering only the transmission of CPM messages. Higher channel load levels resulting from the transmission of additional messages (e.g. CAM or MCM messages) could increase the load and degrade the perception achieved with current ETSI's solution. Our proposal would be more robust again such increase since Table II demonstrates that our proposal significantly reduces the CBR and hence increases the reliability (Table III). Figure 6 also shows that the performance degrades for higher distances. This is due to the propagation effects that impact more the proposal-4m configuration since it is the one that transmits less CPMs. This configuration is hence more sensitive to packet losses.

VI. Conclusions

Collective perception or cooperative sensing will enable connected and automated vehicles to exchange sensor information to improve their perception of the surrounding environment. ETSI is currently defining standards for collective perception message formats and rules to decide when these messages should be generated and what information they should contain. This study shows that the current ETSI solution for collective perception tends to generate significant redundancy in the network that can compromise its scalability without significantly improving the perception performance. This paper has proposed a modification to the ETSI CPM message generation rules to control the redundancy in the network. The evaluation has shown that our proposal significantly reduces the redundancy and channel load and improves the reliability of V2X communications. The proposal maintains the same perception performance (with significantly less messages) than current ETSI's solution for safety-critical short and medium distances, while improving the network scalability. Our proposal has been recently incorporated as part of the ETSI technical report draft as one of the potential solutions to mitigate redundancy in cooperative perception.

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Annex A.4 Publication

Generation of Cooperative Perception Messages for Connected and Automated Vehicles

Gokulnath Thandavarayan, Miguel Sepulcre, Javier Gozalvez

***Abstract*— Connected and Automated Vehicles (CAVs) utilize a variety of onboard sensors to sense their surrounding environment. CAVs can improve their perception capabilities if vehicles exchange information about what they sense using V2X communications. This is known as cooperative or collective perception (or sensing). A frequent transmission of collective perception messages could improve the perception capabilities of CAVs. However, this improvement can be compromised if vehicles generate too many messages and saturate the communications channel. An important aspect is then when vehicles should generate the perception messages. ETSI has proposed the first set of message generation rules for collective perception. These rules define when vehicles should generate collective perception messages and what should be their content. We show that the current rules generate a high number of collective perception messages with information about a small number of detected objects. This results in an inefficient use of the communication channel that reduces the effectiveness of collective perception. We address this challenge and propose an improved algorithm that modifies the generation of collective perception messages. We demonstrate that the proposed solution improves the reliability of V2X communication and the perception of CAVs.**

***Index Terms*— Collective perception, cooperative perception, CPM, connected automated vehicles, autonomous vehicles, CAV, V2X, vehicular networks, ITS-G5, DSRC, C-V2X, ETSI, 5G V2X.**

I. Introduction

Automated vehicles utilize onboard sensors to perceive the surrounding environment and drive autonomously. The perception capabilities of these sensors can be limited for example due to the presence of obstacles (including other vehicles) or adverse weather conditions. Connected and Automated Vehicles (CAVs) can improve their perception capabilities if vehicles exchange information about what they sense using V2X communications. Vehicles can use the exchanged information to detect vehicles or objects that were not detected by their onboard sensors. This is known as cooperative or collective perception. Previous studies [1] have identified the potential of cooperative perception to improve the vehicles' perception beyond the sensors' detection range.

First collective or cooperative perception studies analyzed the advantages and disadvantages of exchanging raw sensor data, processed metadata or compressed data [2]. Exchanging raw sensor data would require large communication bandwidths that cannot be guaranteed by existing technologies (such as DSRC, ITS-G5 or C-V2X) when the network scales. Recent studies have focused on the exchange of information about detected objects including their position, speed and size. For example, the study in [3] compares the perception achieved when the information about the detected objects is attached to existing Cooperative Awareness Messages (CAMs) or is transmitted in separate messages.

Other studies seek to control the information exchanged between vehicles in order to reduce the load on the communications channel. In [4], authors propose that each vehicle should transmit the information about a detected object only if this information is valuable for its neighboring vehicles. Accurately estimating the value of the information in a distributed and highly dynamic environment is a significant challenge. In [5], the same authors partially address this challenge by using deep reinforcement learning to select the information to be transmitted. In [6], authors propose a method to reduce the channel load by transmitting only the most relevant information. This method takes into account the area covered by the sensors that is not covered by nearby vehicles. The work in [7] proposes an analytical performance model for collective perception. The study in [8] shows that existing rules to generate collective perception messages can generate a lot of redundant information in the network as vehicles receive many updates per second about a detected object. Authors propose in [8] a method to reduce this redundancy in order to improve the networks' scalability. Additional redundancy mitigation mechanisms were proposed in [9]. The study in [10] analyzes different content control schemes that decide whether to report or not about certain detected objects based on their distance to the sender vehicle and their impact on position tracking errors. The study determines that objects that are located farther away from the sender but near the edge of the sensors' range should be prioritized. These studies show the need to control the exchanged information without degrading the perception.

The perception also depends on how frequently collective perception messages are generated and transmitted. In principle, a frequent transmission of collective perception messages could improve the perception of CAVs. However, this can be compromised if vehicles generate too many

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messages and saturate the communications channel. An important aspect is then when vehicles should generate the perception messages. ETSI (European Telecommunications Standards Institute) has proposed to date the first set of message generation rules for collective perception [11]. These rules define when vehicles should generate collective perception messages and what should be their content. [12] showed that ETSI generation rules result in the frequent transmission of collective perception messages with information about a small number of detected objects. This results in an inefficient use of the communication channel due to the frequent transmission of packet headers. Overloading the communication channel with frequent messages can also decrease the packet delivery ratio and therefore the effectiveness of cooperative perception. This paper addresses these challenges with an improved algorithm that modifies the generation of collective perception messages and reorganizes their content. To our knowledge, this is the first study that tackles the problem of generating frequent collective perception messages reporting about a small number of objects. The proposal is referred to as *look-ahead* and an earlier version was included in [11]. It modifies the ETSI generation rules to reorganize the transmission of objects in collective perception messages. The reorganization results in that vehicles transmit less messages, and each message includes information about a higher number of detected objects. The proposed solution reduces the channel load and improves the reliability of V2X communications and the perception capabilities of CAVs.

II. Collective Perception Service

ETSI has recently approved a Technical Report that defines the so-called Collective Perception Service (CPS) [11]. The report presents the first proposal to standardize the Collective Perception Message (CPM) format and the CPM generation rules[1]. A CPM contains information about the vehicle that generates the CPM, its onboard sensors (their range, field of view, etc.), and the detected objects (position, speed, size, etc.). In particular, CPM messages include an ITS (Intelligent Transport Systems) PDU (Protocol Data Unit) header and 5 containers: Management Container, Station Data Container, Sensor Information Containers (SICs), Perceived Object Containers (POCs) and Free Space Addendum Container (FSAC). The ITS PDU header includes data elements such as protocol version, the message ID and the Station ID. The Management Container is mandatory and provides basic information about the transmitter, including its type (e.g. vehicle or RSU) and position. The Station Data Container is optional and includes additional information about the transmitter (e.g. its speed, heading, or acceleration). The SIC is optional and can report up to 128 sensors in a CPM. These containers describe the capabilities of the sensors embedded in the transmitting vehicle. The POCs is optional and can report up to 128 detected objects in a CPM. A POC provides information about the detected objects (e.g. their distance to the transmitting vehicle, speed and dimensions), and the time at which the measurements were done. The FSAC is optional and describes the free space areas within the sensor detection areas.

The CPM generation rules define how often a vehicle should generate and transmit a CPM and the information it should include. The current ETSI CPM generation rules [11] establish that a vehicle has to check every *T_GenCpm* if a new CPM should be generated and transmitted, with 0.1s ≤ *T_GenCpm* ≤ 1s. A vehicle should generate a new CPM if it has detected a new object, or if any of the following conditions are satisfied for any of the previously detected objects:

1. Its absolute position has changed by more than 4m since the last time its information was included in a CPM.
2. Its absolute speed has changed by more than 0.5m/s since the last time its information was included in a CPM.
3. The last time the detected object was included in a CPM was 1 (or more) seconds ago.

A vehicle includes in a new CPM all new detected objects and those objects that satisfy at least one of the previous conditions. The vehicle still generates a CPM every second even if none of the detected objects satisfy any of the previous conditions. The information about the onboard sensors is included in the CPM only once per second.

ETSI has proposed to date the first set of generation rules for collective perception. These rules are then considered as benchmark and we next analyze their performance to identify existing challenges and motivate our proposal.

III. Problem statement

Let's consider the scenario in Figure 1 where an ego vehicle has 6 neighboring vehicles. Let's assume that the ego vehicle is equipped with a sensor that has a Field of View (FoV) of 360º and all vehicles move at 70 km/h. The ego vehicle generates CPMs following the current ETSI CPM generation rules and checks the conditions to generate a CPM every *T_GenCpm*=0.1 s. As a result, the ego vehicle includes each detected vehicle in a CPM every 300 ms. Let's suppose, as an example, a scenario where the ego vehicle detects for the first time all neighboring vehicles in a time interval $\tau \leq 0.1$ s. In this scenario (Scenario 1), the ego vehicle generates one CPM every 300 ms, and each CPM includes the information of the 6 detected vehicles (see Scenario 1 in Figure 1). It is though very unlikely that an ego vehicle can detect all its neighboring vehicles in the same time

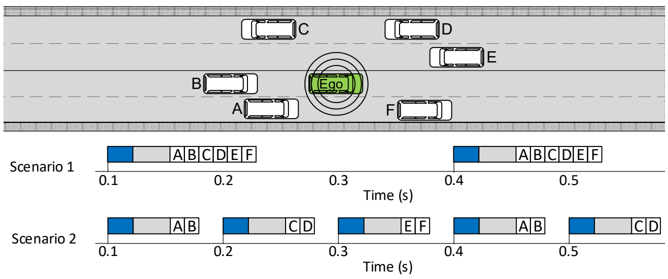

Figure 1. Example to illustrate the problem statement.

[1] The Technical Report in [11] will serve as a baseline for the specification of CPS in ETSI TS 103 324, which has not yet been approved, so the current CPM message format and generation rules are still a proposal.

interval. In a more realistic scenario, vehicles constantly enter and leave the sensor detection range of an ego vehicle at different times. The ego vehicle will then include the detected objects (i.e. vehicles) in different CPMs. Let's consider in Scenario 2 that the ego vehicle detects two different neighboring vehicles in every time interval $\tau = 0.1$ s. In this scenario, the ego vehicle ends up transmitting one CPM every 100 ms instead of every 300 ms like in Scenario 1. In Scenario 2, each CPM includes now information about 2 detected objects every 100 ms instead of 6 every 300 ms (see Scenario 2 in Figure 1). Transmitting more CPMs per second consumes more bandwidth since each CPM includes the ITS PDU Header, the Management and Station Data containers. They occupy around 121 Bytes and are shown in grey color in Figure 1. In addition, each CPM generates protocol headers from the Transport, Network, MAC (Medium Access Control) and PHY (Physical) layers. They occupy around 80 Bytes and are shown in blue color in Figure 1. Figure 1 clearly shows that the transmission of more CPMs with information about less objects (Scenario 2) increases the signaling overhead compared to transmitting less CPMs that contain a larger number of objects (Scenario 1).

We have analyzed and quantified the effects illustrated in the example in Figure 1 by means of simulating an urban and a highway scenario. These simulations consider realistic conditions where the sensors embedded in the vehicles detect the objects and the CPMs are generated following the conditions defined in Section II. For the highway scenario, simulations have been conducted for a 5 km long six-lane highway. We simulated two traffic densities following [13]: 120 veh/km (high density) and 60 veh/km (low density). We configured different speeds per lane to statistically mimic a typical 3-lane US highway. The speed of lanes varies between 118 km/h and 140 km/h for the low traffic density scenario and between 59 km/h and 70 km/h for the high traffic density scenario. For the urban scenario, a Manhattan-like grid scenario with 9x7 blocks is simulated. The size of each block is 433 m x 250 m and each street has 4 lanes [13]. In this scenario, the maximum speed is 70 km/h and two traffic densities are considered: 25 veh/km (low density) and 45 veh/km (high density). In both urban and highway scenarios, the mobility of vehicles is simulated with the road mobility simulator SUMO. To avoid boundary effects, statistics are only collected in the 2 km road segment around the middle of the highway scenario and in the 3x3 blocks in the center of the urban scenario.

V2X communications are simulated using the network simulator ns-3 that is widely used in V2X communications research. All vehicles communicate using the ITS-G5 V2X standard (based on IEEE 802.11p) and therefore transmit using the CSMA/CA (Carrier Sense Multiple Access with Collision Avoidance) protocol. The propagation effects are modeled using the Winner+ B1 propagation model. Winner+ B1 differentiates between Line-of-sight (LOS) and Non-line-of-sight (NLOS) propagation conditions, and hence allows us to consider the strong impact of buildings in urban scenarios on the V2X communications performance. Following [13], the Winner+ B1 model has been adapted for V2V communications by configuring the antenna height to 1.5 m. The transmission power is set to 23 dBm and the packet sensing threshold to -85 dBm. All vehicles transmit using the 6 Mbps data rate (i.e. they utilize QPSK modulation with ½ code rate) and the channel bandwidth and carrier frequency are set to 10 MHz and 5.9 GHz, respectively. The ns-3 simulator has been extended with a CPS component and a sensing module implemented by the authors. The CPS component creates CPM messages based on ETSI's CPM message format [11]. CPM messages are generated following the ETSI CPM generation rules (Section II). The *T_GenCpm* is set to 0.1 s to enable the rapid transmission of newly detected objects and avoid long delays in the transmission of previously detected objects. Vehicles are equipped with a 360º sensor with a sensing range of 150 m [11].

We evaluated the performance of the current ETSI CPM generation rules in the urban and highway scenarios. The evaluation showed that the existing rules generate on average 9.8 and 9.6 CPMs per second per vehicle in the low and high traffic density highway scenarios, respectively. These results reveal that most CPMs are generated every 100 ms independently of the traffic density. In the urban scenario, the average number of CPMs generated per second per vehicle for the low and high traffic density scenarios is equal to 6.1 and 5.7, respectively. In the urban scenario, the CPM generation interval varies between 100 ms and 1 s. This is due to larger variations in the speed of vehicles and in the number of objects detected by each vehicle in the urban scenario (e.g. vehicles tend to concentrate at intersections) than in the highway scenario.

Figure 2 shows the PDF (Probability Density Function) of the number of detected objects by each vehicle and the number of objects included in each CPM when considering the ETSI CPM generation rules in the urban and highway scenarios. The obtained results show that the number of detected objects is non-negligible in both scenarios. The obtained results also show that around 50%-60% of the CPMs contained 4 or less objects in the highway scenario. The figure also reveals that around 50% of the CPMs generated in the urban scenario contained only 1 object while around 90% contained 3 or less objects. The obtained results demonstrate that the number of objects included in each CPM is significantly lower than the number of detected objects in both urban and highway environments. These results clearly confirm the problem previously described and illustrated in Figure 1 for realistic scenarios: the ETSI CPM generation rules generate frequent CPMs that contain a small number of detected objects.

The transmission of frequent and small CPMs adds significant overhead. This overhead increases the channel load and can reduce the reliability of V2X communications and thus degrade the perception of CAVs. To overcome these challenges, we propose an improved algorithm that avoids the frequent transmission of CPMs with a small number of objects.

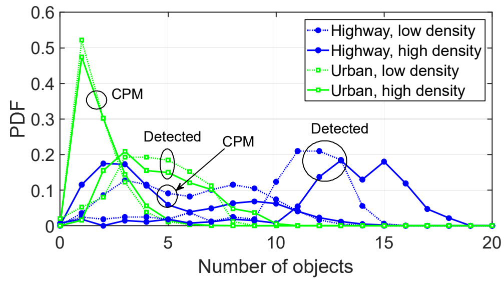

Figure 2. PDF of the number of objects detected by each vehicle and included in each CPM with the ETSI CPM generation rules.

IV. Look-ahead proposal

Our *look-ahead* proposal is designed with the objective to reduce the channel load generated by CPMs while improving the perception capabilities of CAVs. To this aim, we propose a simple yet effective improvement of the current ETSI CPM generation rules to combat its challenges previously discussed. It was a design objective to minimize the changes to the ETSI proposal for higher standardization impact.

In our proposal, vehicles check the conditions to generate a new CPM every *T_GenCpm* following ETSI generation rules. Following these rules, we compute for each detected object the difference in absolute position (ΔP), speed (ΔS) and time elapsed (ΔT) since the last time the detected object was included in a CPM. A new CPM is generated if at least one of the three conditions specified in Section II is satisfied. In other words, the CPM must include the information about the detected objects that satisfy ΔP>4 m or ΔS>0.5 m/s or ΔT>1 s. These are the original conditions of the ETSI rules that we maintain in our proposal. This ensures that our proposal includes each object in a CPM at least as frequently as the ETSI rules. The pseudo-code for this process is shown in lines 1-8 of Algorithm I.

Algorithm I.
Input: Detected objects / Output: Objects (if any) to include in CPM
Execution: Every *T_GenCpm*

1. Set *flag* = false
2. **For** every detected object **do**
3.   Calculate ΔP, ΔS and ΔT since the last time included in a CPM
4.   **If** ΔP>4 m || ΔS>0.5 m/s || ΔT>1 s **then**
5.   Include object in current CPM
6.   Set *flag* = true
7.   **End If**
8. **End For**
9. **If** *flag* = true **then**
10.   **For** every detected object not included in current CPM **do**
11.   Calculate *Next* ΔP, *Next* ΔS and *Next* ΔT
12.   **If** *Next* ΔP>4 m || *Next* ΔS>0.5 m/s || *Next* ΔT>1 s **then**
13.   Include object in current CPM
14.   **End if**
15.   **End For**
16. **End If**

Our proposal is triggered every time a new CPM must be generated by the ETSI rules. Then, our algorithm looks ahead and predicts if any of the detected objects that are not included in the current CPM would be included in the following CPM. The prediction is computed as follows considering that the objects maintain their current acceleration:

$$\boldsymbol{Next\ \Delta P = \Delta P + S \cdot T\_GenCpm + 0.5 \cdot A \cdot T\_GenCpm^2} \quad (1)$$

$$\boldsymbol{Next\ \Delta S = \Delta S + A \cdot T\_GenCpm} \quad (2)$$

$$\boldsymbol{Next\ \Delta T = \Delta T + T\_GenCpm} \quad (3)$$

where S and A are the current speed and acceleration of the detected object. Our algorithm includes in the current CPM (instead of the following one) the detected objects that satisfy *Next* ΔP>4 m or *Next* ΔS>0.5 m/s or *Next* ΔT>1 s. This CPM includes the current information about these objects. Anticipating the inclusion of a detected object in a CPM is proposed to avoid transmitting many CPMs with information about a small number of detected objects. The proposed algorithm is robust against prediction errors resulting from the irregular movement of the detected objects since the worst-case prediction scenario will result in our proposal operating like the ETSI CPM generation rules. The pseudo-code for this anticipatory extension of the ETSI CPM generation rules is described in lines 9-16 of Algorithm I.

V. Evaluation

This section compares our proposal with the ETSI CPM generation rules considering the same highway and urban simulation scenarios described in Section III. In the simulations, vehicles detect objects using their onboard sensors and CPMs are generated following the conditions in Section II.

A. Generation of CPMs

We first analyze how our proposal influences the generation of CPMs. In particular, we study how it impacts the CPM generation rate and the number of objects contained in each CPM. Table I compares the average number of CPMs generated per second per vehicle and the number of objects (i.e. vehicles) per CPM with our proposal and with the ETSI CPM generation rules. The table also reports the difference between the two algorithms. Table I shows that our proposal reduces (between 33% and 44%) the number of CPMs generated per second compared to the ETSI rules. This reduction is achieved by anticipating the transmission of information about detected objects and increasing the number of objects included in each CPM. Table I shows that our proposal augments (between 63% and 110%) the average number of objects included in each CPM in urban and highway scenarios. The improvement is higher in the highway scenario because CPMs are often sparsely transmitted (around 30% above 300 ms) in the urban scenario and each vehicle detects less objects. These effects make it more difficult to group the information about detected objects in less CPMs in the urban scenario.

Table I. Average CPM rate and number of objects in each CPM

Traffic Density	Algorithm	CPM rate		Number of objects	
		Highway	Urban	Highway	Urban
Low	ETSI	9.8 Hz	6.1 Hz	6.1	1.7
	Look-ahead	6.0 Hz	4.1 Hz	11.9	2.9
	Difference	-38.8 %	-32.8 %	+95.1 %	+70.6 %
High	ETSI	9.6 Hz	5.7 Hz	5.1	1.9
	Look-ahead	5.4 Hz	3.9 Hz	10.7	3.1
	Difference	-43.8 %	-31.6 %	+109.8 %	+63.2 %

B. V2X communications performance

The previous section has shown that our proposal reduces the number of CPMs by augmenting the number of objects reported in each CPM. This reduces the communications overhead and decreases the channel load that is here measured with the CBR (Channel Busy Ratio). The CBR is the percentage of time that the channel is sensed as busy and is calculated as in [14]:

$$\boldsymbol{CBR = T_{busy}/T_{CBR}} \quad (4)$$

where T_{busy} is the time (in milliseconds) during which the strength of received signals exceeds -85 dBm. T_{busy} is computed over a period of T_{CBR} = 100 ms. Table II shows that our proposal reduces the CBR between 10% and 23% depending on the scenario and traffic density. This reduction results from transmitting less CPMs and consequently reducing the communications overhead. The reduction of CBR is higher in the urban scenario because CPMs include information about a lower number of objects than in the highway scenario. As a result, the communications overhead represents a larger portion of the transmitted bits in the urban scenario (76% with ETSI rules) than in the highway scenario (49%). These results demonstrate that our proposal reduces the channel load in both scenarios and hence improves the system's scalability.

TABLE II. AVERAGE CBR AND MAXIMUM DISTANCE WITH PDR ≥ 0.9

Traffic Density	Algorithm	CBR		Distance	
		Highway	Urban	Highway	Urban (LOS)
Low	ETSI	29.2 %	12.7 %	132 m	182 m
	Look-ahead	26.1 %	9.7 %	151 m	205 m
	Difference	-10.6 %	-23.6 %	+14.4 %	+12.6 %
High	ETSI	49.4 %	19.9 %	102 m	134 m
	Look-ahead	41.4 %	15.6 %	118 m	162 m
	Difference	-16.2 %	-21.6 %	+15.7 %	+20.9 %

Reducing the CBR and channel load reduces the packet collisions and improves the reliability of V2X communications. We measure this reliability using the PDR (Packet Delivery Ratio) metric that is defined as the probability of correctly receiving a packet at a given distance *d* to the transmitter. The PDR is calculated for a given transmitting vehicle *j* as:

$$\boldsymbol{PDR_j(d)} = \frac{\sum_{i=1}^{N} \boldsymbol{X_{i,j}(d)}}{\sum_{i=1}^{N} \boldsymbol{Y_{i,j}(d)}} \tag{5}$$

where $Y_{i,j}(d)$ is the number of vehicles that are located at a distance between d-$\Delta D/2$ and d+$\Delta D/2$ to the transmitter when the transmitter transmits packet *i*. $X_{i,j}(d)$ is the number of vehicles that successfully receive such packet *i*. *N* denotes the number of transmitted messages and ΔD=25 m. Each value of PDR(d) corresponds to the average PDR at *d* for all transmitting vehicles *j*. Figure 3 depicts the PDR achieved with the ETSI CPM generation rules and our proposal in the urban scenario under low and high traffic densities. The figure plots the PDR under LOS and NLOS propagation conditions between transmitter and receiver. Figure 3 shows that our proposal improves the reliability of V2X communications under LOS thanks to the reduction of the channel load and packet collisions[2]. Under NLOS conditions, the PDR is significantly degraded as it is mostly affected by the propagation conditions due to the presence of buildings. In NLOS conditions, reducing the communications overhead with our proposal does not have a significant positive impact on the PDR.

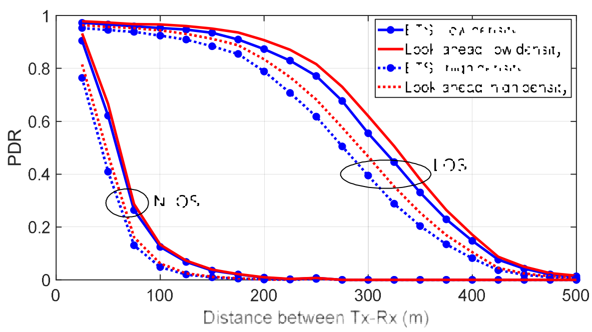

Figure 3. PDR (Packet Delivery Ratio) for the urban scenario.

[2] Similar trends are observed in the highway scenario.

The PDR has a direct impact on the V2X communications range. Table II reports the distance up to which a PDR equal or higher than 0.9 is guaranteed. 3GPP considers this distance as a reference V2X performance metric [13]. Table II shows that our proposal increases this distance compared to the current ETSI CPM generation rules by 12% to 20%. These results show that our proposal increases the reliability of V2X communications thanks to the reduction of the channel load.

C. *Perception capabilities*

The previous sections have shown that our proposal improves the V2X communications performance due to the reduction of the channel load resulting from the reorganization of CPMs. This section evaluates how our proposal impacts the perception capabilities of CAVs. We measure the perception capabilities using the Object Perception Ratio (OPR) metric that is defined as the probability to detect an object within a given time window ΔT thanks to the exchange of CPMs. We consider that a vehicle successfully detects an object if it receives at least one CPM with information about that object during ΔT. The time window has been set equal to the time required by the CPM generation rules for a vehicle to send an update about a detected object considering the speed of the object. The time window ΔT is dynamically computed for each object based on its speed *S* as $\Delta T = T\_GenCpm \cdot \lceil 4 \cdot S^{-1} \cdot T\_GenCpm^{-1} \rceil$, with $\Delta T \leq 1$ s. This computation considers that an object moving at speed *S* is included in a CPM every time it has moved 4 m, and that the CPM period is a multiple of *T_GenCpm*. Considering this dynamic adaptation of the time window, the OPR metric of vehicle *i* and object *j* is:

$$\boldsymbol{OPR_{i,j}(d)} = \frac{\boldsymbol{S_{i,j}(d)}}{\boldsymbol{T_{i,j}(d)}} \tag{6}$$

$T_{i,j}(d)$ is the time during which object *j* is located at a distance between d-$\Delta D/2$ and d+$\Delta D/2$ from vehicle *i*. $S_{i,j}(d)$ is the time during which vehicle *i* has successfully detected object *j* and their distance was between d-$\Delta D/2$ and d+$\Delta D/2$. $S_{i,j}(d)$ is computed taking into account the CPMs received during $T_{i,j}(d)$. Note that $S_{i,j}(d) \leq T_{i,j}(d)$. The OPR metric at a distance *d* is computed as the average value of $OPR_{i,j}(d)$ for all vehicles *i* and all objects *j*. ΔD has been set equal to 25 m.

Figure 4 plots the OPR metric as a function of the distance between the detected object and the vehicle receiving the CPMs. In the urban scenario, we differentiate the cases where the detected object and the vehicle receiving the CPMs are in the same street or in a perpendicular street. This helps us estimate the effectiveness of collective perception as a function of the relative position of the detected object to the vehicle receiving the CPMs, including whether they are under LOS or NLOS conditions. Figure 4 shows that our proposal improves the object perception ratio compared to the ETSI CPM generation rules in both highway and urban scenarios. This is due to two main reasons: 1) our proposal increases the PDR and therefore the probability to correctly receive CPMs, 2) our proposal reorganizes the transmission of detected objects in CPMs. This reorganization increases the average number of times that a detected object is reported in a CPM compared to the ETSI generation rules (by 20% and 10% in the highway and urban scenarios, respectively). This increases the probability to receive information about a detected object and hence the OPR.

Figure 4 shows that the highest perception levels are achieved in the highway scenario where our proposal also obtains its highest improvement compared to the ETSI generation rules. In the urban scenario, buildings significantly attenuate the radio signal and block the sensors field of view. High perception levels can hence only be achieved when the object and the vehicle receiving the CPMs are in the same street. However, the object perception ratio under these conditions is still lower in the urban scenario than in the highway one. This is the case because the urban scenario has lower traffic densities, and consequently, less vehicles detect and report information about each object. Figure 4 also shows that the object perception ratio is significantly degraded (independently of the generation rules) in the urban scenario when the object and the vehicle receiving CPMs are in perpendicular streets. This is because the object and the transmitting vehicle must be in the same street, and thus the transmitting and receiving vehicles are under NLOS conditions (unless the transmitting vehicle is at an intersection). These conditions significantly degrade the PDR and reduce the probability to receive CPMs.

We also analyze the perception capabilities of CAVs by computing the average time between updates that a vehicle receives about a detected object. The updates can be received from any vehicle that has detected the same object. A lower time between updates improves the perception since a vehicle receives more frequently information about a detected object. Figure 5 plots the average time between updates as a function of the distance between the object and the vehicle receiving the CPMs. Figure 5 shows that our proposal reduces the time between updates compared to the ETSI rules, especially at high distances. This is important because the perception capabilities

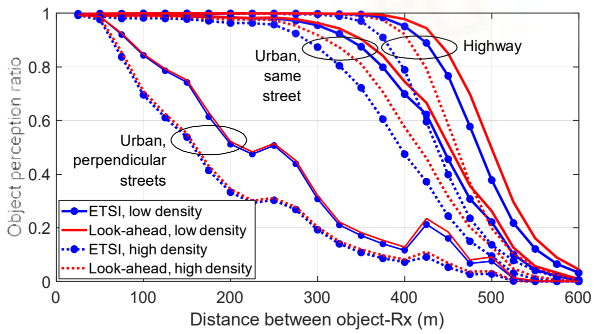

Figure 4. Object perception ratio as a function of the distance between the detected object and the vehicle receiving the CPM.

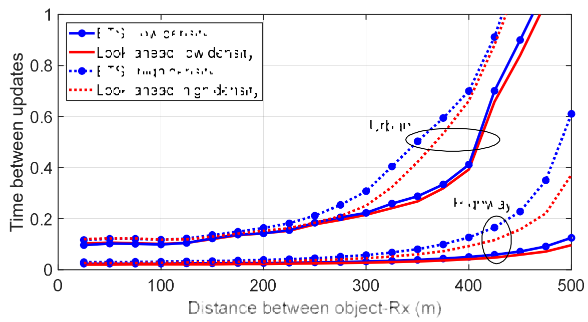

Figure 5. Average time between updates as a function of the average distance between the detected object and the vehicle receiving the CPMs.

of onboard sensors decrease with the distance. This improvement is achieved in both highway and urban scenarios independently of the traffic density.

VI. Conclusions

Cooperative or collective perception improves the perception capabilities of connected and automated vehicles. ETSI has proposed to date the first set of message generation rules for collective perception. These rules have a strong impact on perception since they define when collective perception messages should be generated and transmitted. This study shows that the current message generation rules for collective perception create frequent collective perception messages, and each message reports only about a few detected objects. This increases the communications overhead and degrades the V2X reliability as well as the perception capabilities. This paper proposes an improved algorithm for the message generation rules in collective perception. The proposal reduces the number of collective perception messages per second by reorganizing how information about detected objects is transmitted. Our proposal is able to simultaneously reduce the communications load and overhead, and improve the reliability of V2X communications and the perception of CAVs. This is achieved by reorganizing the transmission and content of CPMs.

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