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# Contextual communication for intelligent transportation systems in hybrid networks

Ameni Chtourou

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# Contextual communication for intelligent transportation systems in hybrid networks

*Communication contextuelle pour les systèmes de transport intelligents dans les réseaux hybrides*

## Thèse de doctorat de l'université Paris-Saclay

École doctorale n° 580, Sciences et Technologies de L'information et de la Communication (STIC)

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**Titre :** Communication contextuelle pour les systèmes de transport intelligent dans les réseaux hybrides

**Mots clés :** Communication véhiculaire, Communication contextuelle, Perception collective, CAM, CPM

**Résumé :**

Un rôle important des C-ITS est d'étendre la perception des usagers individuels de la route afin d'éviter les accidents de la circulation. Une telle perception étendue est construite par l'échange d'informations entre les véhicules, les piétons et les infrastructures à l'aide de différents types de messages, notamment le message de sensibilisation coopérative (CAM) et le message de perception collective (CPM). Bien que les données transportées par ces messages soient critiques, elles consomment des ressources. Par conséquent, la diffusion de ces messages doit être effectuée de manière efficace afin que les exigences des applications de sécurité routière soient assurées et que l'utilisation des ressources soit optimisée.

Cela nécessite que la communication soit sensible au contexte, capable de contrôler les paramètres de communication en tenant compte des exigences de l'application, de la disponibilité des technologies de communication et des ressources radio ainsi que des conditions environnementales (tracé de la route, densité du trafic, présence d'infrastructures en bordure de route, etc.) . La thèse vise à étudier et développer la communication sensible au contexte pour les applications de sécurité routière. L'objectif principal est de proposer et évaluer des algorithmes capables d'optimiser la communication V2X en se basant sur une reconnaissance des contextes.

**Title :** Contextual communication for intelligent transportation systems in hybrid networks

**Keywords :** Vehicular communication, Contextual communication, Collective perception, CAM, CPM

**Abstract :**

An important role of C-ITS is to extend perception of individual road users so that traffic accidents are avoided. Such an extended perception is built by information exchange among vehicles, pedestrians, and infrastructure using different types of messages including cooperative awareness message (CAM) and Collective Perception Message (CPM). While data carried by these messages are critical, they are resource-consuming. Hence, dissemination of such messages must be made in an efficient way so that road safety application requirement is ensured and resource utilization is optimized.

This requires the communication be context-aware, being able to control communication parameters by taking into account application requirements, availability of communication technologies and radio resources as well as environmental condition (road layout, traffic density, presence of roadside infrastructure, and etc.). The thesis targets at studying and developing context aware communication for road safety applications. The main goal is to propose and evaluate algorithms that are able to optimize V2X communication based on a recognition of the contexts.

This thesis is dedicated to my husband Sami, to my little Yasmine...



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# Abstract

One of the key roles of C-ITS is to contribute in extending perception of vehicles and other users so that they can avoid potential accidents. Such an extended perception is built by information exchange among vehicles, pedestrians, and infrastructure using different types of messages including Cooperative Awareness Message (CAM) and Collective Perception Message (CPM). The data carried by these messages are critical, however, they are resource-consuming. Currently, CAMs and CPMs are broadcasted periodically with a minimum frequency of 1Hz. In addition, their frequencies can be adapted based on vehicle dynamics (speed, acceleration and etc) and further with wireless channel condition when a distributed congestion control (DCC) functionality is enabled. However, it might be vital for a vehicle to transmit the messages at a high rate in critical areas, such as intersections, even if there is a risk of observing increased channel utilisation, i.e., higher channel busy ratio (CBR). On the contrary, vehicles with a low risk of collision may reduce their transmission frequency to avoid unnecessary load on the channel (reducing CBR). Hence, dissemination of such messages must be made in an efficient way so that road safety application requirement is ensured and resource utilization is optimized. This requires the communication being context-aware, able to control communication parameters by taking into account application requirements, availability of communication technologies and radio resources as well as environmental conditions (road layout, traffic density, presence of roadside unit (RSU), and etc.). Hence, establishing contexts



that characterize environmental and non-environmental collected information is a key challenge for context-aware communication.

This thesis aims at studying and developing context aware communication for road safety applications. The main goal is to design algorithms that are able to optimize V2X communication based on a recognition of the contexts particularly radio resource availability, environmental condition and application requirements. The work consists of two phases. In the first phase, we identify context aware communication architecture derived from ITS reference architecture and model contexts in terms of 1) application requirement and 2) environmental context. In the first context, we define collision avoidance application requirement and evaluate them against performances of different Cooperative Awareness Service (CAS) strategies. The second context, i.e. environmental context, consists on the presence and availability of road infrastructure equipped with sensors allowing I2V communication to replace V2V communication in that local area. Thanks to its larger communication coverage and sensor field of view, RSU may contribute to Collective Perception Service (CPS) which will result in beneficial impacts including improvement of communication performance, particularly packet delivery ratio, with reduced channel load, while maintaining a high level of awareness rate. The second phase aims at designing, implementing and evaluating algorithms that control CPM generation rate and select data contents taking into account contexts previously identified. *CBR-binary* and *CBR-selective* schemes take into account radio resource availability. *CBR&Infra selective* scheme takes into account not only radio resource utilisation but also if the objects have been announced by a RSU. An extensive simulation have been carried out to evaluate the performances of the schemes. The results present remarkable performance improvements provided by the schemes, particularly in terms of Packet Delivery Ratio (PDR), CBR, and awareness rate compared to the conventional non context-aware CPM generation strategy.



# Résumé

L'un des rôles importants des C-ITS est de contribuer à élargir la perception des véhicules et des usagers de la route afin qu'ils puissent éviter les accidents. Une telle perception étendue est construite par l'échange d'informations entre les véhicules, les piétons et les infrastructures à l'aide de différents types de messages, notamment le message de coopération (CAM) et le message de perception collective (CPM). Bien que les données incluses dans ces messages soient critiques, elles consomment beaucoup de ressources radio. Actuellement, les CAM et les CPM sont diffusés périodiquement avec une fréquence minimale de 1 Hz. De plus, leurs fréquences peuvent être adaptées en fonction de la dynamique du véhicule (vitesse, accélération, etc) et en outre avec l'état du canal sans fil lorsqu'une fonctionnalité de contrôle de congestion distribué (DCC) est activée. Cependant, il peut être vital pour un véhicule de transmettre ses informations à un débit élevé dans les zones critiques, telles que les intersections, même si cela risque d'entraîner un taux d'occupation de canal (CBR) plus élevé. Au contraire, les véhicules à faible risque de collision peuvent réduire leurs fréquences de transmission pour éviter une charge inutile sur le canal radio. Par conséquent, la diffusion de tels messages doit être effectuée d'une manière efficace afin que les exigences d'applications de la sécurité routière soient garanties et que l'utilisation des ressources soit optimisée. Cela nécessite que la communication soit contextuelle, capable de contrôler les paramètres de communication en tenant compte des exigences de l'application, de la disponibilité des technologies de communi-

cation et des ressources radio ainsi que des conditions environnementales (configuration des routes, densité du trafic, présence d'infrastructures en bordure de route, etc.) . Par conséquent, établir des contextes qui caractérisent les informations environnementales et non environnementales collectées est un défi majeur pour la communication contextuelle. Cette thèse vise à étudier et à développer une communication contextuelle pour les applications de sécurité routière. L'objectif principal est de concevoir des algorithmes capables d'optimiser la communication V2X en se basant sur la reconnaissance des contextes, notamment la disponibilité des ressources radio, les conditions d'environnement et les exigences des applications. Le travail comprend deux phases. Dans la première phase, nous identifions une architecture de communication contextuelle et nous modélisons des contextes en termes de 1) exigences applicatives et de 2) contexte d'environnement. Pour le premier contexte, nous définissons les exigences d'applications pour éviter les collisions et les évaluons par rapport aux performances de différentes stratégies de service de sensibilisation coopérative (CAS). Le second contexte, c'est-à-dire le contexte environnemental, consiste à la présence et la disponibilité d'infrastructures routières équipées de capteurs (RSU) permettant à la communication I2V de remplacer la communication V2V dans cette zone locale. Grâce à sa plus grande couverture de communication et son plus large champ de vision de capteurs, RSU peut contribuer au service de perception collective (CPS) qui aura des impacts bénéfiques, notamment l'amélioration des performances de communication, en particulier le taux de réception de paquets, avec une charge de canal réduite, tout en maintenant un taux élevé de perception collective. La deuxième phase vise à concevoir, développer et évaluer des algorithmes qui contrôlent la fréquence de génération et le contenu des messages CPM en tenant compte des contextes préalablement identifiés. Les algorithmes *CBR-binary* et *CBR-selective* prennent en compte la disponibilité des ressources radio. Quant à l'algorithme *CBR&Infra selective*, il prend en compte non seulement l'utilisation des ressources radio mais aussi si les objets ont été déjà perçus par un RSU. Une simulation approfondie a été réalisée pour évaluer les

performances de ces algorithmes. Les résultats présentent des améliorations de performances remarquables, en particulier en termes de ratio de réception de paquets (PDR), de CBR et de taux de perception par rapport à la stratégie de génération de CPM non contextuelle conventionnelle.



# Publications

## Conference papers:

- Chtourou, A., Merdrignac, P., Shagdar, O. (2020, June). Context-Aware Communication for V2V Collision Avoidance Applications. In 2020 International Wireless Communications and Mobile Computing (**IWCMC**) (pp. 1958-1963). IEEE.
- Chtourou, A., Merdrignac, P., Shagdar, O. (2021, April). Collective Perception service for Connected Vehicles and Roadside Infrastructure. In 2021 IEEE 93rd Vehicular Technology Conference (**VTC-Spring**) (pp. 1-5). IEEE.

## Journal paper:

- Chtourou, A., Merdrignac, P., Shagdar, O. (2021, October). Context Aware Content Selection and Message Generation for Collective Perception Services. In 2021 electronics journal, Special Issue 'Wireless Communication Technology in Intelligent Transport Systems' (**Impact factor : 2.4**).





# Abbreviations

ABS : Automatic Breaking System  
ADAS : Advanced Driver Assistance System  
AIFS : Arbitration Inter-Frame Space  
AIFSN : Arbitration Inter-Frame Spacing Number  
BTP : Basic Transport Protocol  
CAM : Cooperative Awareness Message  
CAS : Cooperative Awareness Service  
CBR : Channel Busy Ratio  
CPM : Collective Perception Message  
CPS : Collective Perception Service  
C-ITS : Cooperative Intelligent Transportation Systems  
DCC : Decentralized Congestion Control  
DENS : Decentralised Environmental Notification Service  
DSRC : Dedicated Short Range Communication  
ESP : Electronic Stability Program  
ETSI : European Telecommunications Standardisation Institute  
FOV : Field Of View  
GNSS : Global Navigation Satellite System  
GPS : Global Positioning System

IoT : Internet of Things  
ITS : Intelligent Transportation Systems  
ITS-S : Intelligent Transportation Systems Station  
ISO : International Standardization Organization  
I2V : Infrastructure To Vehicle  
LDM : Local Dynamic Map  
LTE : Long-Term Evolution  
MAC : Medium Access Control  
MANET : Mobile Ad Hoc Network  
MEC : Mobile Edge Computing  
MSDF : Multi Sensor Data Fusion  
OBU : On Board Unit  
PDR : Packet Delivery Ratio  
PIR : Packet Inter reception Time  
PLCP : Physical Layer Convergence Protocol  
RTL : Road Line Topology  
RSU : Road Side Unit  
R-ITS-S : Roadside Intelligent Transportation Systems Station  
SIFS : Short Inter-Frame Space  
SPAT : Signal Phase And Timing  
TCP : Transmission Control Protocol  
TLM : Traffic Light Maneuver  
TTC : Time To Collision  
TTI : Time To Inform  
TTS : Time To Stop  
UDP : User Datagram Protocol  
VANET : Vehicular Ad hoc Network

VLC : Visible Light Communication

V2C : Vehicle To Center

V2N : Vehicle To Network

V2P : Vehicle To Pedestrian

V2R : Vehicle To Roadside

V2V : Vehicle To Vehicle

V2X : Vehicle To Everything

V-ITS-S : Vehicle Intelligent Transportation Systems Station



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# Chapter 1

## Introduction

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## 1.1 Context and motivation

Despite technological and strategic advances in road safety, the majority of transportation systems around the world are still suffering from serious safety and efficiency issues. Worldwide, road accidents, caused essentially by human errors, kill more than a million of people every year and leave around 20 to 50 million injured or disabled persons. This is the main cause of deaths among young people aged between 5 and 29 years [1]. Complementary, the report published by the National Observatory of Road Safety ONISR [2] shows that the road fatality rate in France is increasing, an increase that affects particularly pedestrians and cyclists. Besides to road safety, the driving style and traffic jams have a negative impact on fuel consumption and air pollution. In fact, more than half of global oil production goes to fuel the transportation sector [3] .

To overcome these issues, numerous initiatives have been taken by governments, associations and car manufacturers to improve road safety and to solve the previously mentioned traffic problems. Among these initiatives, we cite: awareness and prevention traffic campaigns, sanctions for violations of traffic laws, the integration of means of protection on board vehicles, the improvement of road infrastructure as well as public transportation systems.

Intelligent Transportation Systems (ITS) are developed with the idea of introducing a field of new information technologies applied to transportation systems using different technologies such as: GPS tracking, obstacle and pedestrian detection, vehicle control, etc. They aim to improve road safety and traffic efficiency by reducing the number of accidents on the roads. In recent years, Advanced Driver Assistance Systems (ADAS) appeared on vehicles with different functionalities such as the ABS (Automatic Braking System) and ESP (Electronic Stability Program) for help when braking. In order to perform the functionality of ADAS, vehicles must be equipped with a set of synchronized and connected sensors via vehicular networks. Implementation of these systems is delicate

because they require compatibility, synchronization and calibration of sensors, as well as the use of real-time systems and realistic simulators to reflect real-life issues.

### 1.1.1 Vehicular networks

A subset of ITS, co-called Cooperative ITS, put a focus on information exchange among vehicles and other entities for road safety and traffic fluidity.

When the network node is a vehicle, it will be equipped with an OBU (on-board unit), which is provided with V2X communication capabilities and also calculates, displays and exploits all information needed for C-ITS applications. On the other hand, a RSU is made up of a set of devices installed on the road side, it can be intermediary to exchange data between vehicles and central entities or itself can be installed with C-ITS applications and communicate with vehicles [4]. In order to ensure communication of vehicular nodes, two main types of technologies are considered: short distance wireless communication technologies, which allow direct communications among vehicles and RSUs, and cellular communication technologies. The IEEE 802.11p (ITS G5 in Europe) or LTE-V2X standards belong to the former type of technologies particularly operate in the 5.9 GHz band dedicated to C-ITS. To ensure reliable vehicle to vehicle (V2V) and vehicle to roadside (V2R) communication, the United States reserve a spectrum between 5.895-5.925 GHz band for the ITS service. As for Europe, a frequency bandwidth of 70 MHz (5.855 - 5.905 GHz) allocated. While USA privileged a use of Cellular V2X (C-V2X) for direct communications and the Europe stays technology agnostic. On the other hand, V2X communication may use cellular technologies (4G/5G) to exchange data. A use of cellular communication is particularly straight-through for Vehicle to Center (V2C) communications or for Vehicle to everything (V2X) in sparse traffic density. The 5G technology brings further benefits thank to its emerging functionalities such as Mobile Edge Computing (MEC), slicing, and so on.

### 1.1.2 C-ITS Services

The connected and automated vehicles will be equipped with new intelligent communication systems allowing them to operate autonomously, that is, to perceive their environment, to communicate with each other but also with infrastructure including base stations, mobile edge and cloud entities in order to make intelligent decisions based on their actual situations.

A combination of communication with detection and perception capabilities provided by the set of sensors integrated in vehicles allows development of several C-ITS services and use cases. A wide range of C-ITS services for road safety and efficiency has been identified in the literature and specified by different standardisation organisations (ETSI, ISO, etc.). The followings are key C-ITS services that have been specified.

- Cooperative Awareness Service (CAS) is to support road safety applications, such as emergency vehicle warning, slow vehicle indication and so on, by allowing connected vehicles and other road users exchange CA messages. A CAM contains status and attribute information of the originating ITS-S. For vehicle ITS-Ss the status information includes time, position, motion state, etc. and the attribute information includes data about the dimensions, vehicle type and role in the road traffic, etc. CAMs are periodically generated and the period can be adapted based on the vehicle's speed and etc. Upon reception of a CAM, the receiving ITS-S becomes aware of the presence, type, and status of the originating ITS-S.
- Collective Perception Service (CPS) is, similar to CAS, to support road safety applications to increase the vehicles' and other road users' awareness, more precisely perception, regarding its environment by exchange of Collective Perception Messages (CPM). While CAMs are transmitted by connected entity to announce its presence and status, CPMs are used to announce list of objects perceived by sensors of the connected entity. CPMs can be more efficient in a hybrid traffic scenario con-



sisting of both connected and non-connected road users. Similar to CAMs, CPMs are periodically broadcasted by all the C-ITS-S that have CP service capability.

- Decentralised Environmental Notification Service (DENS) are to alert road hazard or abnormal traffic conditions, such as accident, wrong way driving, traffic light violation, stationary vehicle, traffic jam. DENS is provided through DEN messages, that details the target event, particularly identification of the event, event detection, time, position and so on. Unlike CPMs and CAMs, DENMs are generated only upon a request of the application that detected the event. DENMs can be forwarded over multiple hops, if necessary, depending on the type of the event.
- Traffic Light Maneuver Service (TLM) provides safety related information for supporting traffic participants (vehicles, pedestrians, etc.) to execute safe maneuvers within an intersection area. The TLM service informs in real-time about the operational states of the traffic light controller, the current signal state, and the residual time of the state before changing to the next state, the allowed maneuver and assistance for crossing. Additionally the TLM service foresees the inclusion of detailed green way advisory information and the status for public transport. TLM service is provided through the Signal Phase and Timing (SPAT) message by a roadside infrastructure, which is used to convey the current status of one or more signalized intersections.
- Road Line Topology Service (RLT) is to manage the generation, transmission and reception of a digital topological map. It includes the lane topology for e.g. vehicles, bicycles, parking, public transportation and the paths for pedestrian crossings and the allowed maneuvers within an intersection area or a road segment. The RLT service is provided through so-called MAP message. Similar to SPAT, MAPs are generated by roadside infrastructure and disseminated locally.

## 1.2 Problem statement

ITS is a very complex system because of the heterogeneity of the environmental conditions (road topology, infrastructure availability, weather conditions, etc.), the diversity of applications (road safety, traffic efficiency, automated driving, etc) and the availability of different types of communication technologies and protocols (ITS-G5, cellular technologies, etc.). Therefore, ITS necessitates V2X communication system be intelligent, particularly context-aware. While a large number of contexts can be imagined for ITS, for road safety applications, we believe that i) application requirements, ii) availability of communication technologies and radio resources, as well as iii) environmental condition (road type, traffic density, presence of roadside infrastructure, and etc.) are the most important contexts. The first context concerns understanding requirements of the applications, which can be expressed by different performance indicators. The second context is about understanding the communication capability of the current system and availability of the network and resource. For example, radio resource availability can be measured by e.g., channel busy ratio (CBR) for the ITS-G5 and C-V2X technologies. Finally, as environmental condition, one may consider the road layout or presence of roadside infrastructure e.g., roadside unit (RSU) in the surrounding environment.

Among the different types of services listed in the previous subsection, Cooperative Awareness and Collective Perception Services have important roles for ITS because they are to extend the perception of road users, and consequently to avoid accidents. Nevertheless, although data carried by CAMs and CPMs are critical, they are resource-consuming because all vehicular nodes share the same wireless channel and broadcasting of these messages may saturate the wireless channel especially in a dense traffic situation. In the case of CPMs, because several vehicular nodes could inform about the same objects detected by their sensors it is possible that the CPS overloads radio channel with unnecessarily redundant information. Indeed, it is been reported by ETSI in [5], when

CPMs are mainly transmitted by vehicles, the number of objects per CPM can be low but redundant and particularly the messages updates can be very frequent (10 messages per second).

It is obvious that in order to ensure safety of road users, application requirements must be satisfied in all conditions. Despite of its benefits for reducing channel load, the current CAM/CPM generation strategies do not consider their impacts on the road safety applications. Indeed, it might be vital for a vehicle to transmit its message at a high rate in critical areas, such as intersections, even if this may result in higher channel load. On the contrary, vehicles with a low risk of collision may reduce their transmission frequency to avoid unnecessary load on the channel. Hence, focusing on road safety applications, the first question we intend to answer is: what are the application requirements to be met with a communication system?

Once application requirements are known, external factors such as environmental conditions and available communication technologies are major aspects which can impact information dissemination. In particular, when RSU mounted with sensors such as cameras equip the roadside infrastructure, they may extend vehicles' perception due to their larger field of view, communication coverage and processing capacity compared to vehicles. However, such installation may not be present everywhere. Therefore, it is very important to study each traffic situation and make specific decisions. Thus, the second questions to be answered is: what are the impacts of the environmental conditions, in particular the availability of roadside infrastructure, on information dissemination?

Finally, different communication flow, e.g V2V and I2V communication, may be present simultaneously and convey redundant information. Indeed, considering CPS, a road object, e.g. a vehicle or a pedestrian, can be detected and broadcast at the same time from vehicles and roadside sensors. Such redundancy can have positive effects to improve object detection accuracy but also increases usage of communication channel. Thus, priority rules have to be established, for instance, by disabling CPM transmissions at

vehicles in an area covered by an RSU. Then, the third question to be answered is: How to select the transmitting node (vehicle or RSU) and what content to put on a CPM in order to avoid redundancy, i.e. channel congestion, while ensuring a high level of awareness?

The objectives of the current PhD project is to propose solutions in order to answer the previously mentioned questions by enabling adaptive communication control and making the best decision for each traffic situation based on a recognition of the context.

### 1.3 Thesis methodology and contributions

In order to answer the previously mentioned questions and address the thesis problematic, we followed a methodology depicted in Fig. 1.1.

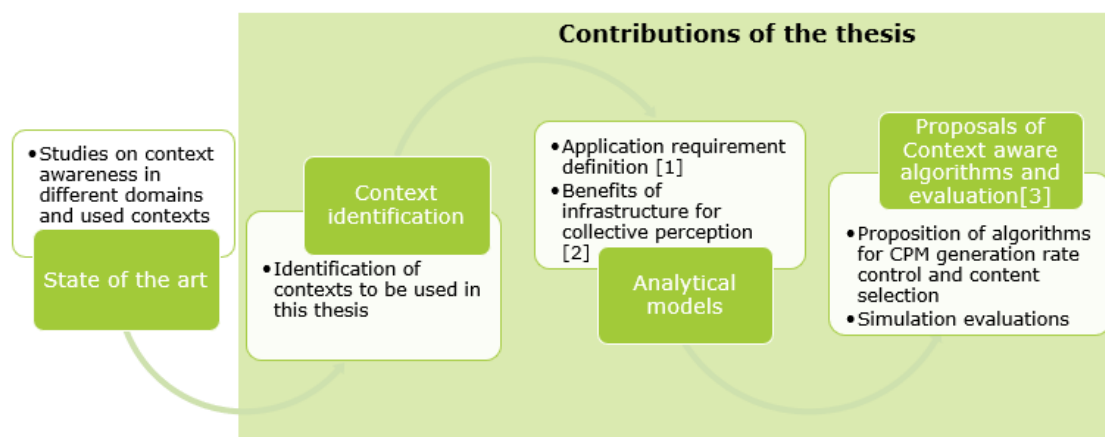


Figure 1.1: Thesis methodology and contributions

We first review studies on context awareness applied to different domains with the focus on cooperative intelligent transport systems domain and provide details about the most used contexts. We classify related works to 3 main categories depending on the objective of using context awareness : road safety, V2X communication optimization and security. We also investigated on the main contexts that are used to build context aware-

ness and impact communication system. We categorize them to 3 contexts: resource availability describing channel status and resource utilization, application requirement for safety and non safety applications and finally external factors consisting on different environmental information impacting driving situation such as weather condition, road side infrastructure, road density and etc.

Derived from this study, we identify contexts that should be used in this work regarding a selected use case / scenario. More specifically, targeting road safety applications, we focus on collision avoidance application for different critical scenarios especially insertions / intersections where potential collisions lead to dangerous situations.

Then, we build our analytical models that aim to model the previously identified contexts. Particularly, application requirement definition model was provided to identify V2V collision avoidance application needs [6]. We propose to express collision avoidance application requirement in terms of communication performance metric that could be understandable by communication system. Also, we build environmental condition context consisting on the availability of roadside infrastructure allowing the use of V2I besides to V2V communication. More precisely, we show the benefits of using RSU for collective perception in terms of not only the number of transmitted objects per message but also the optimization of radio resource utilization. We used Markov chain model for analysing MAC performances and we propose mathematical models to analyse the number of obstacles in the field of view of vehicular nodes [7].

Finally, we focus on context aware communication control for collective perception using I2V and/or V2V communications. In this part, we propose to design, develop and simulate intelligent context aware algorithms for CPM generation rate control and content selection. More precisely, based on the results of our analytical model showing the benefits of RSU availability in terms of data efficiency and resource utilisation when RSU contribute to CPM generation, we intend to manage radio resources by switching I2V and/or V2V communications when a RSU is available in the environment [8]. Such al-

gorithms aim to propose a trade off between data redundancy/situation awareness and radio resource utilisation. To show the effectiveness of our algorithms, we evaluated them against a non context-aware algorithm where CPMs are broadcasted periodically via simulation using VEINS simulator. VEINS is a hybrid simulator based on two well established simulators: a network simulator OMNETPP and a traffic simulator SUMO.

The key contributions of this thesis are the following:

- After reviewing the existing efforts on context awareness and used contexts, we identified the context aware system architecture that enables context-aware communication conforming with the ETSI C-ITS reference architecture. Once the architecture is selected, the contribution aims to identify contexts that impact V2X communication including road safety application requirement, radio resource utilisation and infrastructure availability. Contexts can then support control of communication systems and their parameters, particularly cooperative awareness and collective perception services.
- The second challenge consists on building analytical models to determine 1) application requirement and 2) benefits of RSU availability for collective perception. First, we develop a mathematical model on road-safety application requirement particularly for intersection collision avoidance. After identifying the application requirement, we show that existing DCC algorithms that take into account only resource availability are not sufficiently context aware and do not meet the application requirement, demonstrating a need of considering more than one context in controlling a communication system. Second, we show the impact of considering RSU availability on the environment on collective perception. We compare CPMs generated by vehicles against CPMs generated by RSU in terms of number of objects, data redundancy and channel occupation.
- The third challenge concerns the design and development of context awareness to

control communication system targeting the identified contexts. The main goal is to design algorithms that are able to optimize communication over heterogeneous networks based on a recognition of the contexts application requirements, environmental condition (presence of infrastructure) and resource availability. First, we propose an algorithm to control CPM generation and content selection based on channel status particularly radio resource availability. Also, we propose an algorithm to control CPM generation and content selection based on infrastructure availability allowing the possibility to switch V2V and I2V communications when RSU . Finally, a multi-context aware algorithm is proposed using the combination of previously mentioned contexts. These algorithms are implemented and evaluated using VEINS simulator. The conducted evaluations confirm the effectiveness of these algorithms showing their benefits to improve the reliability of the CP service.

## 1.4 Work environment

This research work was carried out at VEDECOM institute, which is French institute for public-private partnership research and training dedicated to sustainable, ecological, autonomous and shared mobility. It's main research activities are divided into 3 domains: i) electrification, ii) connected and automated vehicles and iii) new mobility solutions and shared energies (see Fig. 1.2).

The first domain i.e. electrification is interested in electrified vehicles, reducing their total cost and improving their performance. The second domain, i.e. connected and automated vehicles, aims to improve road safety and traffic efficiency using vehicle connectivity and shared mobility. The last domain intends to study how to better share roads and cars, optimize parking spaces and develop digital services to help with mobility. Besides its research activities, VEDECOM proposes training sessions that bring a high level of expertise in its three fields of research.

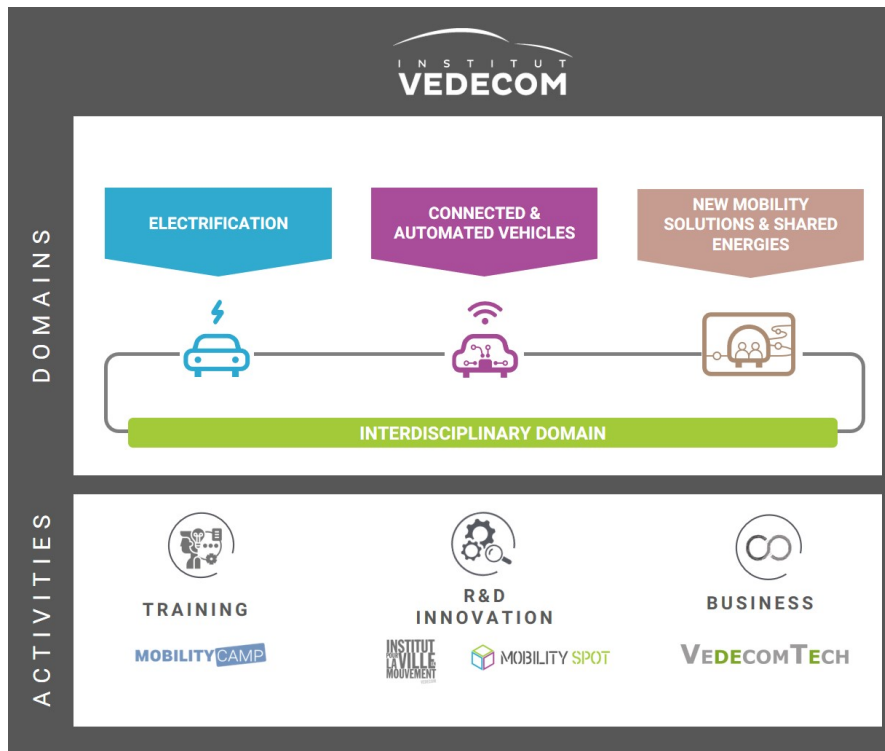


Figure 1.2: VEDECOM activities

More precisely, this thesis is done within REVECOM team (REliable VEHicular COmmunication for intelligent Mobility) that belongs to the second domain, connected and automated vehicles. REVECOM deals with different challenges and its research topics focus on studying vehicular communication vectors (5G, LTE, G5, V2X, etc) and their hybridization. Research activities are made up of 4 tasks:

- Lot 1 is dedicated to research activities on innovative solutions for vehicular communications. This research work is carried out within this lot.
- The activities of lot 2 include the deployment of a hybrid V2X communication platform (4G / 5G, ITS-G5, VLC), the development of V2X performance measurement tools and the definition of test and experimentation methodologies.
- Lot 3 focuses on cyber security research activities



- Lot 4 is interested in standardisation activities for 3GPP and ETSI organisations.

The partners of this work are both industrial and academic. The industrial partners include automotive suppliers and vehicle manufacturers : Renault, Stellantis, Continental, TDF and Transdev while academic partner is the university of Versailles Saint Quentin-En-Yvelines (UVSQ) and INRIA.

## 1.5 Manuscript organisation

The rest of this manuscript is organized as follows: Chapter 2 reviews C-ITS applications and services, ITS reference architecture and standardization activities on facilities layer. We detail channel congestion problem in VANET and describe Distributed Congestion Control (DCC) framework standardised by ETSI. Then, we review related works on context awareness especially applied to ITS domain and study different contexts that are used in these works. At the end of this chapter, we summarize studied papers and provide perspectives. Chapter 3 consists on analysing context aware communication for collision avoidance applications. First, we identify context aware system architecture derived from ETSI reference architecture. The latter is extended by the implementation of context awareness in the management layer allowing information exchange with other layers to control critical communication parameters. Also, contexts that support collision avoidance application are defined: 1) application requirement, 2) radio resource availability and 3) environmental context. In the second part, we focus on providing analytical models to formulate application requirements and the impact of RSU in providing CPS. The first challenge is to define road safety application requirement in terms of communication metrics particularly minimum required packet delivery ratio and packet inter reception time, that are derived from collision risk calculation. The second challenge consist on modeling environmental context, i.e. RSU availability, comparing CPS provided by vehicles and by RSUs, particularly their impacts on extending

vehicles' perception and showing its benefits on CPM dissemination for V2V and I2V communications. An evaluation study of the proposed models is provided. In chapter 4, we present different schemes that aim to control CPM generation rate and to select CPM contents by taking into account the previously modeled contexts. In chapter 5, we focus on simulation evaluations of the proposed schemes using the hybrid simulator VEINS. The evaluation study compares these algorithms with default algorithm (where context-awareness is not considered) to highlight their better performances in terms of PDR, CBR and awareness rate when one or more context are applied. Finally, we will conclude our work and provide some perspectives in chapter 6.

## Chapter 2

# State of the art : Cooperative Intelligent Transport Systems and context awareness

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## 2.1 Introduction

This chapter consists of 2 main parts. In the first part, we review ITS concept in addition to C-ITS services and applications. Then, we highlight the challenging characteristics of ITS environment, especially the properties of vehicular ad hoc networks (VANET). More specifically, we provide an overview of V2X communications between vehicular nodes. We present also main standardization and research efforts to propose an adequate communication architecture and protocols. Besides, we put a focus on the existing standards for different C-ITS services (CAS, CPS, DENS, AS, and etc). The second part is dedicated to review context awareness as the solution for optimized V2X communications. We first present the definitions of context awareness in general, and context aware computing. Then, we focus on existing efforts on context awareness in several domains particularly ITS domain. Also, we investigate on used contexts. Finally, the chapter is concluded with the main insights learnt from this literature review and the main research subject that are to be addressed in this thesis.

## 2.2 Cooperative Intelligent Transport Systems (C-ITS)

Intelligent transportation systems (ITS) apply information and communication technologies to transport, such that connected and automated cars make mobility safer, more efficient and more sustainable. These solutions are made to reduce accidents caused by human errors. In fact, through ITS, using in-vehicle applications, drivers/automated vehicles can receive fresh information not only on road hazards but also on the currently applied road regulations and traffic rules. Particularly, such systems will automatically alert emergency and safety services in the event of an accident/hazard on the road. This information exchange between road users forms the so-called Cooperative Intelligent Transport Systems (C-ITS).

Particularly, C-ITS rely on wireless communications and data exchange between vehicles and/or between vehicles and other road entities. Vehicular communications are used for a large range of applications which can be divided into the following three categories: applications targeting road safety, applications for traffic management and finally applications for entertainment and user's comfort:

- Road safety, the ultimate goad of ITS, which aims to reduce accidents number and enhance the safety of drivers by enabling warning alerts in case of dangerous situations. These applications include pre-crash sensing, lane change assistance, collision warning and so on, as shown in Fig. 2.1 Safety services are supported with the transmission of Collective Perception Messages (CPMs), Decentralized Environmental Notification Messages (DENMs) and Cooperative Awareness Messages (CAMs) (Basic Safety Messages (BSMs) in the US). CAMs are sent periodically by the vehicles and contain mobility information such as speed and position.
- Traffic efficiency that enhance traffic flow and route optimization by supporting drivers/automated vehicles to reduce the traveling time spent on the road.
- Entertainment and user comfort enabling infotainment and comfort services for passengers as well as drivers such as file and video streaming sharing and internet access.

A large part of C-ITS research is dedicated to vehicular networks, particularly vehicular ad-hoc networks (VANET), which is a Mobile Ad Hoc Network (MANET), where vehicles are the principal type of network nodes. VANET is a dynamic network with a variable density that could be implemented in urban areas, rural areas, highways,etc. Although it is seen as an application of MANET, it presents some particular characteristics:

- High mobility: Its main difference with other mobile networks is its high mobility and dynamic topology where vehicles' velocity can reach 130 Km/h in highways

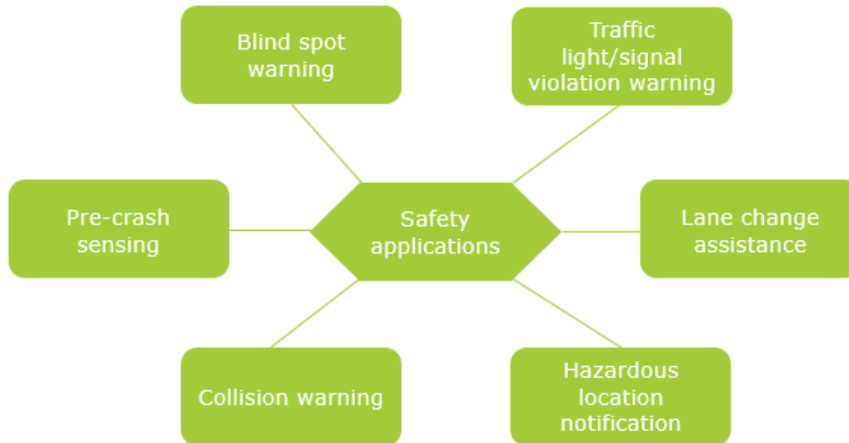


Figure 2.1: Road safety applications in VANETs

while it does not exceed 50 Km/h in urban areas. Although vehicle movements are relatively predictable, the impact of mobility on network connectivity remains one of the major difficulties of vehicular networks.

- Frequent disconnection: where vehicular nodes frequently lose connection due to the highly dynamic topology, changes on their connectivity status and the presence of obstacles and constraints imposed by road topology.
- Unknown network size: a vehicular network could be implemented in a small zone (e.g. highway), for a city or even for a country which lead to an unbounded geographical network size.

These special features lead to study vehicular communication architectures enabling reliable information exchange between all types of network nodes. Particularly, it is necessary to ensure information exchange between vehicular nodes that could be not only among vehicles but also with roadside unit (RSU), pedestrians and etc., leading to the following vehicle to everything (V2X) communication possibilities as illustrated in Fig. 2.2:

- Vehicle To Vehicle (V2V) communication : this mode allow direct communication

between vehicles forming an ad-hoc network without the need to rely on a fixed infrastructure.

- Vehicle To Pedestrian (V2P) communication mode allow information exchange between vehicles and pedestrians.
- Vehicle To Infrastructure (V2I) communication: allowing vehicles to communicate with a fixed infrastructure. If the infrastructure is a roadside infrastructure or roadside unit, the mode is called vehicle to roadside (V2R) communication. Vehicle to Network (V2N) is another form of V2I, in which vehicles communicate with an entity (MEC, V2X application server, etc.,) installed in the network particularly via the 5G technology. Finally, yet another form of V2I is vehicle to centre (V2C) communication mode, which allows vehicles to communicate with a central entity, typically installed in the Internet.

It should be noted that a VANET is a distributed network that may be built upon V2V, V2R, and/or V2P communication links. On the other hand, a vehicular network can be centralised or decentralised or hybrid network that may have all modes of V2X communication.

## **2.3 C-ITS standards and solutions**

### **2.3.1 C-ITS reference architecture**

In order to successfully implement C-ITS applications and reach their benefits in terms of mobility and safety, vehicular nodes will have to cooperate, and exchange reliable and accurate information via several services including CAS and CPS. This requires a clear definition and assignment of behaviors and responsibilities of each entity. To this end, ETSI and ISO have defined the C-ITS reference architecture [9], for vehicular



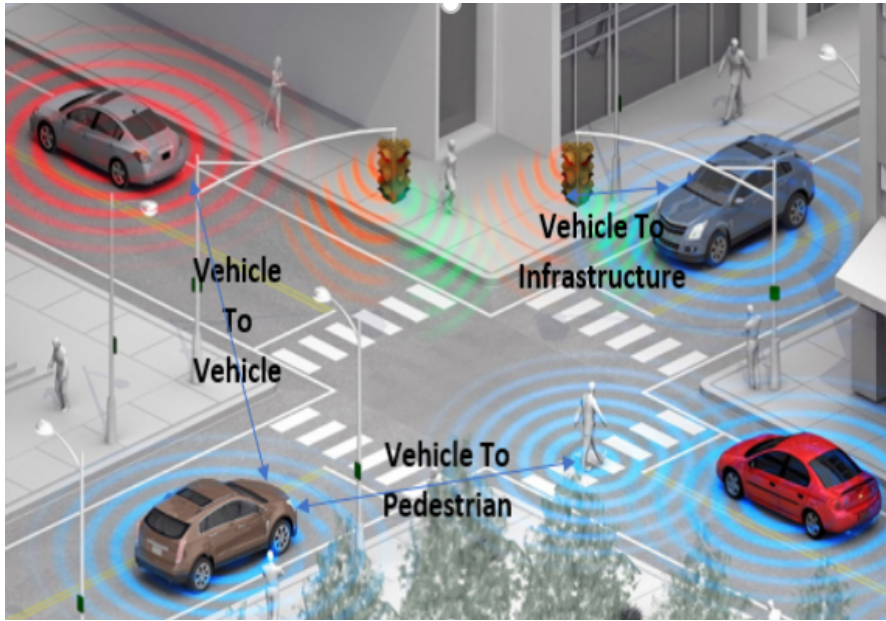


Figure 2.2: Hybrid VANET architecture in Intelligent Transportation Systems

communications that consists of four horizontal and two vertical layers as illustrated in Fig 2.3.

- Access layer represents PHY and MAC layers in OSI architecture. It contains different wireless communication technologies for C-ITS including ITS-G5, C-V2X, 4G and 5G.
- Networking & Transport layer combines Network and Transport layers of OSI architecture. It is responsible for the delivery of messages across the network using two categories of transport and networking protocols for IP and non-IP communications. Particularly, in adding to the well known User Datagram Protocol (UDP), Transmission Control Protocol (TCP), and Internet protocol suits, the reference architecture introduces protocols that are dedicated to geographically scoped message dissemination, namely basic transport protocol (BTP) and Geo-Networking protocol.

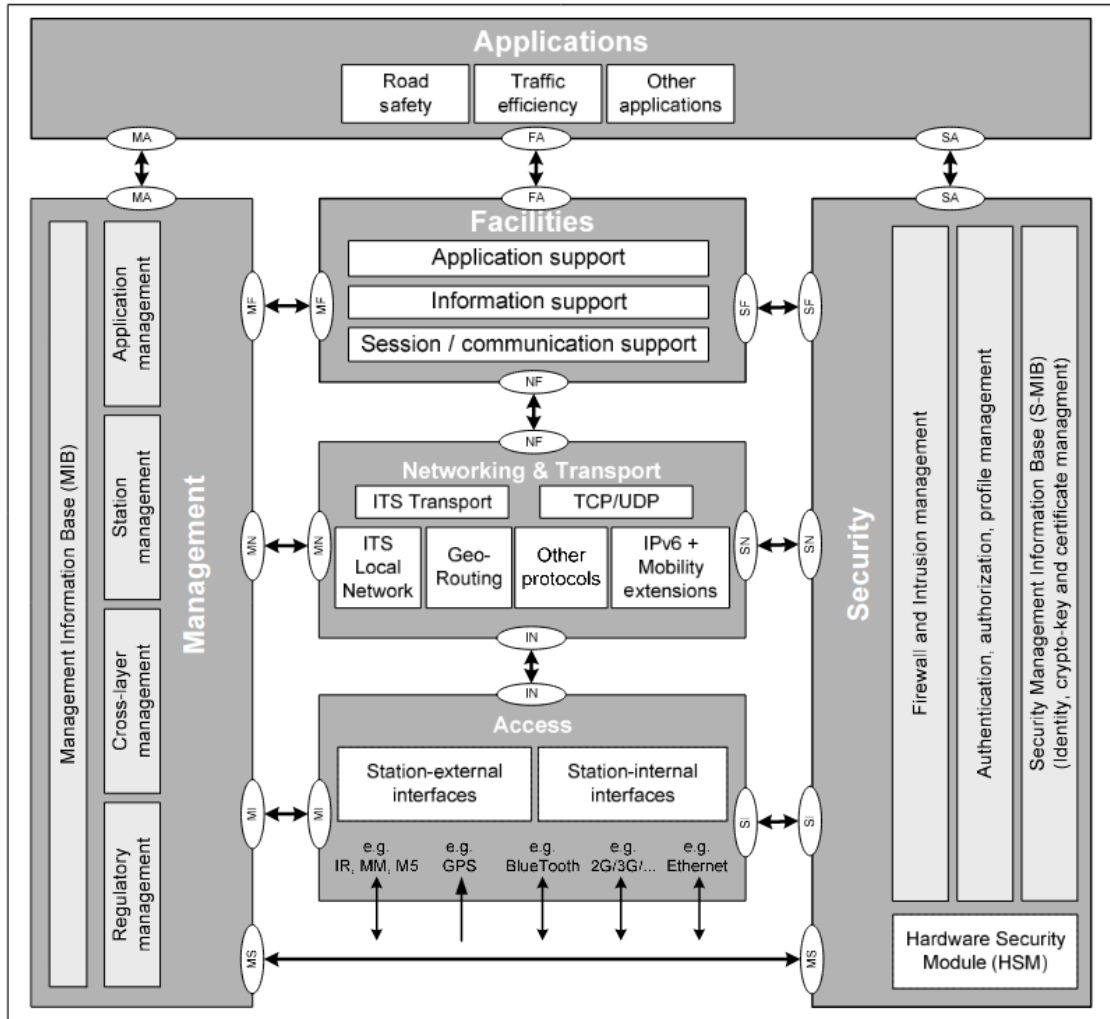


Figure 2.3: ETSI C-ITS reference architecture

- Facilities layer corresponds to the Session and Presentation layers of the OSI stack, which aims at providing communication and information supports to the C-ITS applications. To this end, a number of facility layer services have been specified, including CAS, CPS, DENS and Local Dynamic Map (LDM).
- Application layer includes different C-ITS applications that can be for road safety, traffic efficiency, and etc.

Besides the above mentioned horizontal layers, the reference architecture defined two

vertical layers namely management and security. The security layer provides security measures to ensure to key security roles, particularly authenticity, integrity, confidentiality of the communication system and data. The management layer is responsible for cross-layer operations. Specifically, besides facilitating information exchange among different layers, this layer is to optimise the behavior of the overall communication system.

### **2.3.2 Access layer technologies**

The high QoS requirements of new vehicular applications have led to new standardization efforts to develop the next generation of V2X communications which will support these new applications using wireless and cellular technologies.

#### **ITS-G5**

ITS-G5 is the European standard of a radio access technology for V2V and V2R communication using the dedicated C-ITS 5.9GHz frequency band. The ITS-G5 technology is based on the IEEE 802.11p standard, which enhances the classical IEEE 802.11 a standard needed to allow efficient V2V and V2R direct communication in highly mobile scenarios. Same to the other IEEE 802.11 technologies, the underlying channel access method of the IEEE 802.11p is the Carrier Sense Multiple Access protocol with Collision Avoidance (CSMA/CA) protocol.

#### **C-V2X**

In order to be aligned with the expansion of vehicular communication and the evolution of their use cases, 3GPP defined V2X standard based on LTE as the underlying technology in 2017 with the Release 14 (Rel-14) specifications. It is generally referred to as "cellular V2X" (C-V2X) or LTE-V2X to differentiate itself from the 802.11p based V2X technology. In addition to the direct communication (V2V, V2I), C-V2X also supports wide area

communication over a cellular network (V2N). C-V2X is defined to take advantage from two types of communication on a single technology platform: (1) a direct short-range mode operating over the 5.9 GHz spectrum and not requiring any network coverage or subscription, (2) a long-range mode using traditional cellular networks resources using mobile network operator licensed spectrum

## **4G/5G**

Cellular technologies have witnessed dramatic growth over the past two decades. These advancements target to obtain high quality of service with high throughput, low latency and increased reliability. Considering these advances, automotive research institutes and industrial communities show their interest towards exploiting this efficient communication technology to satisfy vehicular services requirements in terms of support of multi-hop, trusted, secure and low latency communications with high reliability. In this context, a growing interest is being shown for considering these cellular networks mainly 4G (LTE) and 5G and compete with other technologies such as IEEE 802.11p based technologies. The aim of 5G is to promote ultra-low latency, massive machine type communication and enhanced mobile broadband with high throughput. The 5G network capability promises a performance jump compared to 4G in terms of data rate ( $> 1$  Gbps per user ; 10 times more compared to LTE), extra low latency (1ms vs. 10ms in LTE), better energy efficiency and etc.

### **2.3.3 C-ITS services and messages**

The main goal of vehicular communication is to enhance road safety as well as traffic efficiency using C-ITS services. The latter allow the exchange of mobility information through various types of messages (CAM, CPM, DENM, etc) between vehicular nodes (vehicles, RSU, pedestrians, etc) in a single hop broadcast. In this section we describe some of the facilities layer services.

## Cooperative Awareness Service (CAS)

CA service aims to allow connected vehicles exchange their information via CAMs [10]. CAMs are broadcast periodically from vehicles to their surrounding entities in their local area and contain mobility information such as vehicle type, speed, position, and etc. The general structure of a CAM is depicted in Fig. 2.4. As it can be seen, a CAM is composed of one ITS PDU header and other containers including a basic container, one high frequency container, eventually one low frequency container and one or more special containers.

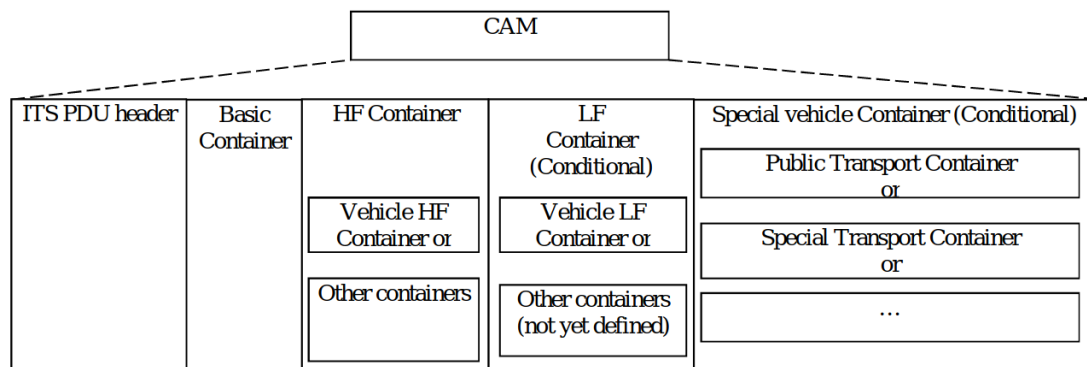


Figure 2.4: General structure of CAM

The CAM generation rules is managed by the CA service and it determines the time interval between two consecutive CAM generations with the consideration of the upper and lower limit intervals which are :  $T_{GenCamMin} = 100$  ms and  $T_{GenCamMax} = 1000$  ms. CAM generation shall be triggered by the originating ITS station (ITS-S) depending on its dynamics based on the following rules:

- Its absolute position has changed by more than 4m since the last time a CAM was transmitted;
- Its absolute speed has changed by more than 0.5m/s since the last time a CAM was generated;

- Its absolute velocity has changed by more than 4 degrees since the last time a CAM was generated;
- The time elapsed since the last time a CAM was transmitted is equal or greater than 1 second.

### **Collective Perception Service (CPS)**

Although CAS is expected to improve road safety, such an improvement is possible only when the C-ITS penetration is sufficiently high i.e. the majority of the vehicles on the road are V-ITS-Ss. It is realistic to expect that the C-ITS penetration rate will gradually, maybe slowly, increase and hence, roads will be shared by ITS-Ss and non-communicating vehicles and VRUs for many years.

Potential benefits of collective perception built exploiting vehicle-embedded sensors and V2X communications have been presented in [11, 12, 13]. CPS is to greatly improve road safety even in hybrid traffic conditions, i.e., communicating and non-communicating vehicles coexist [14]. ETSI is currently developing standards of CPS [5] specifying a message format of CPMs, which are to be exchanged between CPS protocols, and the message generation rules that CPS protocols have to respect.

A CPM is composed of one common ITS PDU header and multiple containers, namely, a management container, sensor information containers, perceived object containers, and free space addendum containers, which constitute together the CPM parameters. (see Fig.2.5) [5]. The ITS PDU header includes the information of the protocol version, the message type and the identification of the ITS-S. The management container provides information regarding the station type and the reference position of the message generator. The sensor information container is to provide the sensory capabilities of the ITS-S. Depending on the number of sensors, a CPM may have one or more sensor information containers. A perceived object container is added for every object that has been

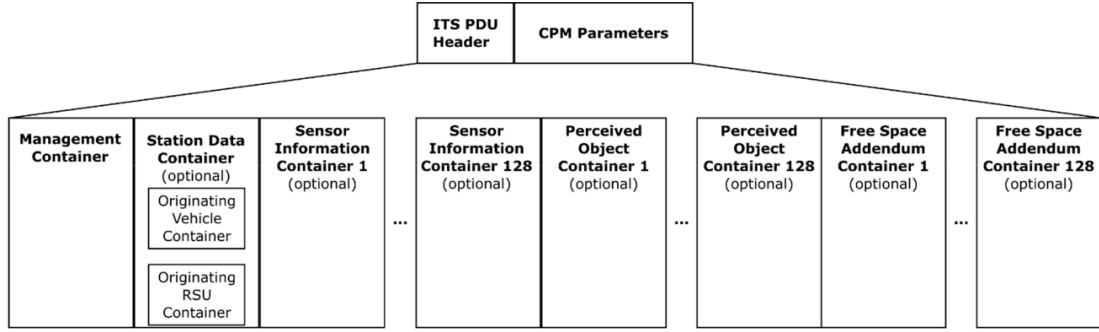


Figure 2.5: CPM general structure

perceived by the ITS-S. It provides information about the detected object, such as its position, dimension, velocity, acceleration, and type etc. Finally, a CPM can have a free space addendum containers to describe changes to a computed free space description.

The CPM generation rules define when the vehicle should generate a CPM and what information should be included. Similar to CAM generation rules, a vehicle should check every  $T_{GenCpm}$  if a new CPM should be generated.  $T_{GenCpm}$  should be set between the boundaries  $T_{GenCpmMin} = 100$  ms and  $T_{GenCpmMax} = 1000$ ms.

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 degrees since the last time its data was included in a CPM;
- The last time it was included in a CPM is equal or exceeds 1000ms.

Nevertheless, when the traffic is dense and the number of sensor-equipped V-ITS-S is high, CPMs tend to be radio resource-consuming and can create a huge load to the

radio channel, leading to performance degradation [15]. Potential impacts of CPMs on wireless channel occupation as well as vehicles' situation awareness have been reported in the ETSI technical report [5].

### **Decentralized Environmental Notification Service (DENS)**

Decentralized Environmental Notification Service (DENS) is a facilities layer service which provide services to modules of ITS application layer through DEN messages (DENM) (see Fig. 2.6). The latter are sent by C-ITS stations to describe events related to different use cases, mainly for road safety and traffic efficiency in order to alert vehicles about dangerous situations. A DENM contains information related to a road hazard or an abnormal traffic condition, such as its type and its position. At the receiving side, the DEN basic service of a receiving ITS-S processes the received DENM and provides the DENM content to the relevant ITS-S application. This ITS-S application may present the information to the driver if information of the road hazard or traffic condition is assessed to be relevant to the driver. The driver is then able to take appropriate actions to react to the situation accordingly.

A new DENM is generated based on a request from an application. Each new DENM is assigned with an action ID, which is the combination of an ITS-S ID and a sequence number. The ITS-S ID is the station ID that detected the event. For each new DENM, unused value is assigned as the sequence number. The originating ITS-S may detect an evolution of the event after the DENM trigger. The ITS-S application provides the update information to the DEN basic service. The DEN basic service then generates an update DENM. The reference time, the time at which the DENM is generated by the DEN basic service, identifies the DENM update referring to a specific action ID. The action ID remains unchanged for DENM update, as long as the station ID remains unchanged. Moreover, the action ID remain unchanged when the validity duration is updated, as long as the station ID remains unchanged. In between two consequent DENM updates,



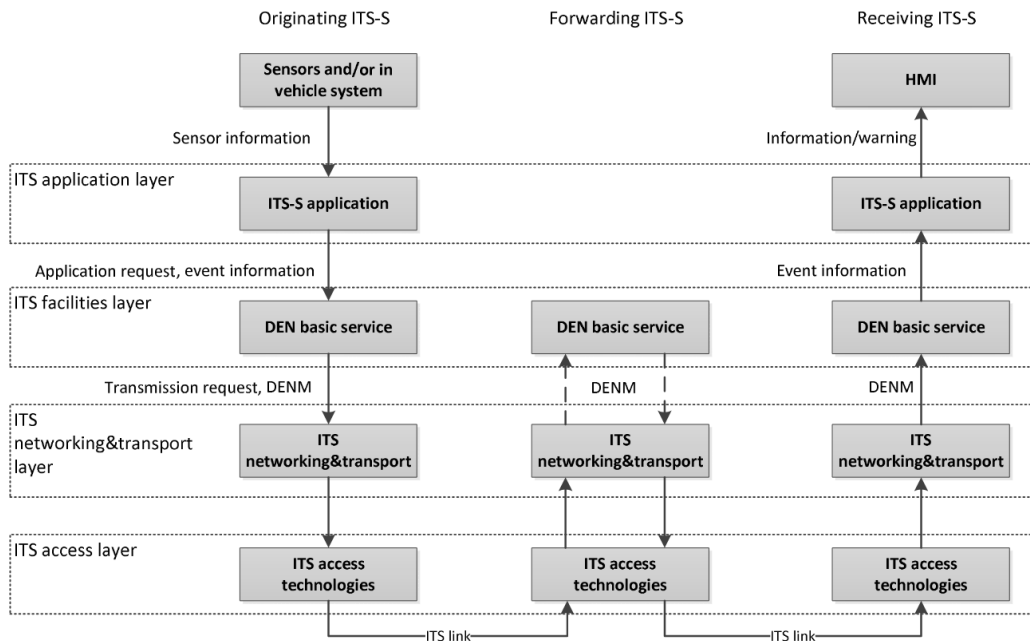


Figure 2.6: General data flow for ITS-S application supported by the DEN basic service

a DENM may be repeated by the DEN basic service of the originating ITS-S at a pre-defined repetition interval, in order that new ITS-Ss entering the destination area during the event validity duration may also receive the DENM. If ITS-S application at the originating ITS-S requires the repetition of DENM, it shall provide repetition Interval and repetition Duration values in the request. The DENM termination indicates the end of the detected event. A DENM termination is either a cancellation or a negation. Cancellation DENM can only be transmitted by the originating ITS-S that originally requested the DENM trigger. Negation DENM can be transmitted by other ITS-Ss.

### Service Announcement (SA)

The service announcement (SA) service is responsible for generating and receiving SAM messages. As illustrated in Fig. 2.7, it interfaces with the SA management entity, which is responsible for the registration/update/deregistration of applications that requires transmissions and receptions of SAMs.

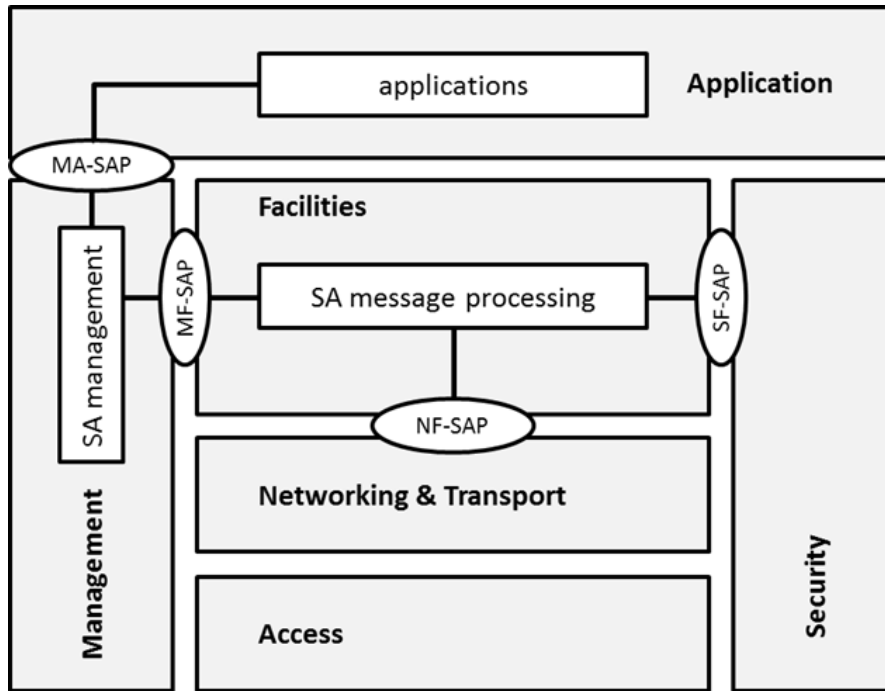


Figure 2.7: SA in ITS reference architecture

Service announcement message (SAM) is specified in [16]. Some of the applications out of the basic set of applications require Service user ITS-Stations have the knowledge that a certain service of interest is provided by service provider ITS-S. ITS protocol stack supports push and pull mechanisms in order to allow an ITS station to identify the availability of ITS services. SAM is then used to provide the push functionality by specific services. The SA service is provided with so-called Minimum Dissemination Area (MDA) by the ITS application. The SAMs are then subject to be disseminated to reach any ITS-S in the MDA. To do so the SA service provides the MDA as the destination area to the Geonetworking protocol in order to allow reforwarding if necessary.

### Infrastructure service

The infrastructure services refer to facilities layer entities that manage the generation, transmission and reception of infrastructure related messages from the infrastructure

(C-ITS-S or R-ITS-S) to V-ITS-S or vice-versa. The specification of the facilities layer infrastructure services is being carried out in [17]. Infrastructure service messages include signal phase and timing (SPAT), Signal State Message (SSEM), and etc. The common challenge of these services is to improve the aspect of mobility in city environments by communication between infrastructure, especially a traffic light controller, and vehicles, informing the drivers of the road configuration, traffic light status, and allowing prioritised intersection crossing to vehicles with special roles such as public transportation. As illustrated in Fig. 2.8, interfacing with applications, and the network layer entities, the infrastructure service (IS) is responsible for generating and receiving infrastructure service messages. The following message types are specified as the following:

- Signal phase and time (SPAT). The corresponding service entity is referred as "Traffic Light Maneuver" TLM.
- MAP (intersection description): The corresponding service entity is referred as "Road and Lane Topology" - RLT service.
- Infrastructure to Vehicle Information message (IVIM): The corresponding service entity is referred as "Infrastructure to Vehicle Information"
- SREM (Signal request message): The corresponding service entity is referred as "Traffic Light Control" .
- SSM (Signal State message): The corresponding service is referred as " Traffic Light Control"

### **2.3.4 Distributed congestion control**

As described in the previous section, connected vehicles and infrastructures have to periodically broadcast messages such as CAM, CPM, and SPaT. Furthermore, if a road

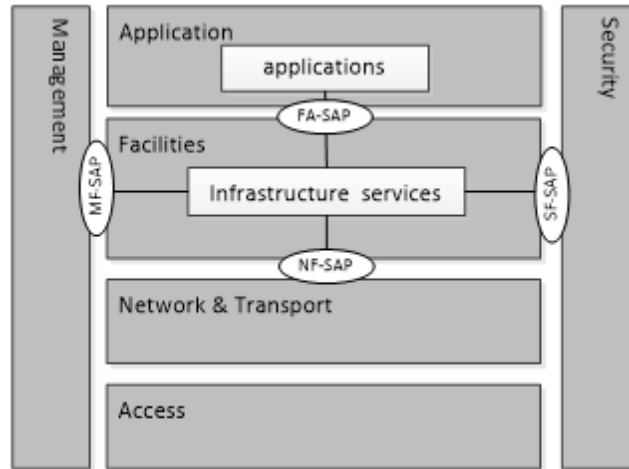


Figure 2.8: Infrastructure Services in ITS reference architecture

hazard is detected, other types of messages such as DENMs will also be broadcasted and maybe forwarded over multiple hops. It is most likely that these messages will be disseminated primarily over the C-ITS dedicated 5.9GHz channels. Due to the limited radio resource and increased transmission activities, it is known that the communication system will face so called channel congestion issue, that leads to performance degradation in terms of reliability and latency. Indeed, in [18], the author showed that vehicular communication present very poor performances for PDR (less than 25%) as well as transmission delay (around 1 second) when node density is very high. Consequently, it is of prime importance to manage the channel access control and radio resources in order to ensure a reliable and efficient vehicular communication. Hence, a robust and efficient congestion control algorithm is required to avoid this limitation. In [19], the authors reviewed works on congestion control in VANETs and classified them to 3 categories: reactive, proactive and hybrid congestion control strategies. In the first category, control actions are only taken when a congestion occur. The proactive category consists on calculating channel load based on different transmission parameters lading to a maximum congestion limit. The hybrid strategy combines both active and proactive strategies in

order to control several parameters [20].

### DCC framework for ITS

To enable efficient congestion control in C-ITS, ETSI specified a cross-layer Distributed Congestion Control (DCC) framework on top of the ITS reference architecture [21].

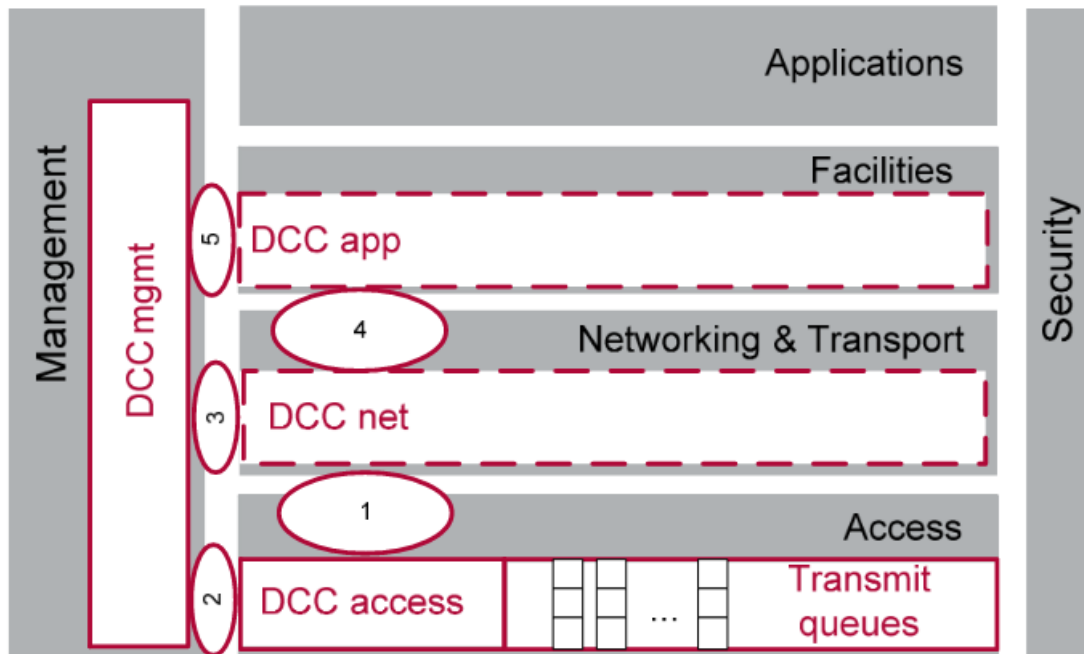


Figure 2.9: DCC architecture in ITS protocol stack

Figure 2.9 illustrates the general DCC architecture in the ITS reference architecture as well as the distribution of its modules within the different layers of ITS reference architecture. This DCC mechanism is composed of DCC-ACC which is implemented at the level of the Access layer, DCC-NET implemented at the level of the Networking layer, DCC-FAC implemented at the Facilities layer, and DCC-CROSS implemented at the Management layer, the latter ensures the exchange of information between different layers for an optimized communication. DCC-ACC is responsible for channel monitoring and access layer DCC such power control and data rate. DCC-NET implements network

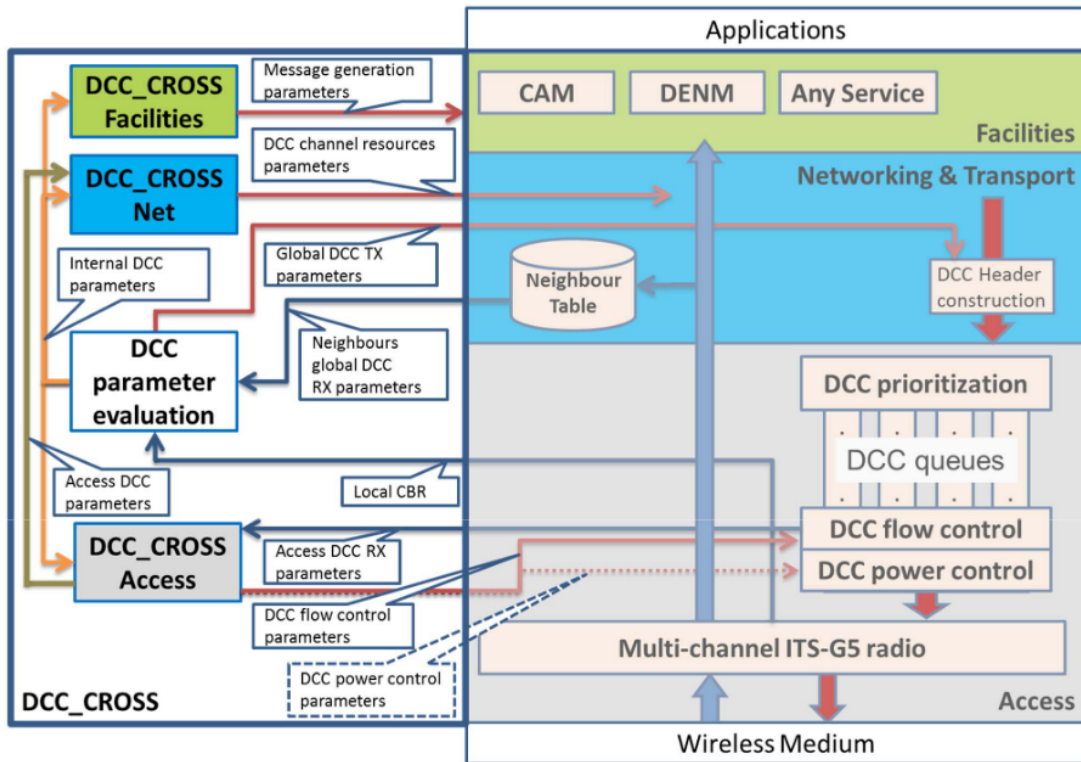


Figure 2.10: Overview of the DCC in an ITS-S

layer DCC such as optimisation of routing parameters. DCC-FAC implements facilities layer DCC including message generation rates of CAM, CPM, DENM, and so on. It is expected that DCC implemented in the different layers operate based on the information, particularly channel status information from the access layer, obtained via DCC-CROSS.

### DCC mechanism concept

As mentioned, in vehicular communications, since safety messages such as CAM, CPM and DENM are broadcasted locally by each node without a central coordination, a DCC mechanism is needed to address such challenge. In fact, the DCC mechanism fundamental concept aim to adjust system radio resource utilisation such that a moderate overall channel load is maintained with the cooperation of every vehicular node that should

measure its current channel load.

In USA, SAE DCC [22] controls the transmission of Basic Safety Messages (BSM) in terms of message rate, transmission power and etc, using several metrics including Vehicle Density in Range, Channel Busy Percentage (CBP), and Packet Error Ratio (PER). In particular, message rate is controlled using Vehicle Density in Range metric. In Europe, a DCC algorithm is seen as a control process that takes into account the channel load as an input parameter and decides, based on a load threshold value, for each vehicular node its possible resource utilization as an output. In order to measure channel load, The Channel Busy Ratio (CBR) is the most common metric and CBR is calculated as follows:

$$CBR = \frac{T_{busy}}{T_{monitor}}$$

The CBR could be high due to the high density of the network or the high message generation rate, or both of them. The CBR threshold value is of prime importance and should be specified in a careful way as it will determine the channel load status, either idle or busy. In fact, a low CBR threshold allow eventually unwanted connections with distant nodes which probably lead to increase the channel load.

### **DCC reactive and adaptive control**

A DCC algorithm control could be either reactive or adaptive. In one hand, reactive DCC algorithms basically adjust the appropriate message generation rate based on the current CBR following a look up table as depicted in Table. 2.1. The latter specifies the three logical channel states: relaxed, active and restricted (see Fig. 2.11:

- The relaxed state indicates a low CBR (channel idle) below a minimum threshold value. Here, no restrictions on message transmission interval or message transmission rate are imposed by the DCC algorithm.

- The active state which is divided to other sub-states (active1, active2, etc) indicates that the channel load is medium and moderate restrictions are imposed.
- The restricted state considers the channel is overloaded (CBR is above a maximum threshold value) and serious restrictions on resource utilization and message generation rate should be taken.

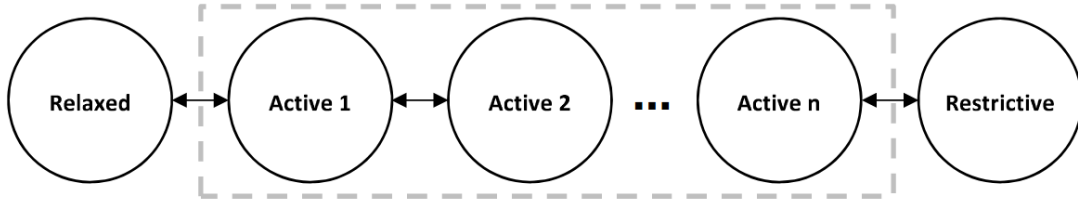


Figure 2.11: Outline of reactive DCC approach

Table 2.1: Reactive DCC lookup table

States	CBR (%)	$T_{off}$ (ms)	$R^{ms}$ (Hz)
<i>Relaxed</i>	[0,19[	60	16.7
<i>Active<sub>1</sub></i>	[19,27[	100	10.0
<i>Active<sub>2</sub></i>	[27,35[	180	5.6
<i>Active<sub>3</sub></i>	[35,43[	260	3.8
<i>Active<sub>4</sub></i>	[43,51[	340	2.9
<i>Active<sub>5</sub></i>	[51,59[	420	2.4
<i>Restricted</i>	[59,100]	460	2.2

On the other hand, adaptive control approach adjust the output parameter, e.g. message generation rate of each node on the network so that a moderate total channel load do not exceed the target value  $CBR_{target}$ . For example, LIMERIC [23] is an adaptive rate-control algorithm that control message generation rate based on the adaptation of each node message rate regarding its current CBR. The final channel load converges to a target value. Particularly, for a given node, its message rate denoted as  $r_j(t)$  is adapted every



$\lambda$  time using the following linear equation :

$$rj(t) = (1 - \alpha)rj(t - 1) + \beta(CBR_{target} - CBR_{measured}(t - 1))$$

Here,  $CBR_{target}$  is the target channel load.  $\alpha$  and  $\beta$  are the parameters that adapt stability, fairness and steady state convergence.

### **Related works on DCC**

A DCC algorithm could adjust various parameters from different layers. For instance, at facilities layer, message generation rate could be controlled so that radio resources are optimized [24, 25, 26]. It has been shown that controlling only the generation rate of messages can mitigate channel congestion [23, 27]. However, since a significant reduction in message generation rate may have a negative impact road safety, it is desirable to control other parameters in parallel including transmission rate, transmission power and carrier sense [28, 29].

The authors of [30] studied various transmission techniques and proposed a message transmission technique that prioritize important packet information in order to ensure system reliability. Indeed, despite of the importance of transmitting/receiving fresh and updated mobility information for each vehicular node, a high message transmission rate may saturate the channel especially in dense scenarios.

At the Access layer, Aygun et al. [31] proposed an adaptive control algorithm, which determines the transmission power for a given road environment. The algorithm is combined with the LIMERIC [23] so that the CAM messages are controlled at both the Facilities layer and the Access layer. Also, the authors of [32] compared the impacts of controlling different parameters including transmission rate and control. They showed that adding a control on the rate of generation of CAMs to the power transmission control can significantly reduce the load on the radio channel. Andreas et al. [33] proposed

a DCC algorithm that uses the DCC-gatekeeper, which is introduced between the network layer and the Access layer and which makes it possible to control the frequency of multi-hop packet forwarding. Bellache et al. [34] worked on a Distributed Congestion Control (DCC) algorithm at the GeoNetworking level (Network layer) for DENM dissemination. They proposed an improvement of the multi-hop transmission contention-based (CBF) through a congestion control feature. In order to use the channel efficiently, their proposal adapts the number of re-transmissions according to the channel load state.

### **Redundancy mitigation techniques**

The emergence of cooperative perception to support automated driving has led to a higher demand in terms of data transfer between road users. Due to the limited capacity of any communication media, new approaches are needed to ensure an efficient usage of available communication resources while maintaining high reliability for vehicular applications. To address such limitation, a number of efforts have been made to establish message generation rules and to determine the information that should or should not be included in CPMs [35, 5, 36] by taking into account the channel load status. In fact, it has been shown that controlling CPM content can have a positive impact on channel usage [35, 37]. Some studies demonstrated significant information redundancy in CPMs transmitted by different vehicles due to their overlapping sensors field of view (FOV) [38, 39, 7]. Such a situation may load the communication channel with unnecessary redundant information, leading to reduce the service reliability. Moreover, the authors of [36] carried out a simulation study evaluating the impacts of different CPM transmission strategies on channel load and situation awareness. The results showed that, due to dynamically changing traffic situations, CPMs tend to be generated at the highest frequency, 10Hz, even if the transmitters are configured to adapt their message generation frequency. Thus, more advanced policies that can mitigate information redundancy among messages while maintaining perception reliability are needed [40]. To address the channel congestion

problem, in its technical report TR 103 562 [5], ETSI studied redundancy mitigation techniques and suggested some rules based on frequency, dynamics, confidence, entropy, object self-announcement and distance. Although no clear conclusion on which of such rules should be implemented, the report highlights advantages and drawbacks of each of these approaches and leaves the opportunity for further research. In [41], the authors proposed to assess channel congestion in order to adapt object inclusion policies.

To reduce such redundancy among messages, few approaches relying on data content selection have been introduced. These proposals seek to evaluate importance of data content by empirical thresholds [40] or based on probabilistic models [42, 43]. Table 2.2 gives an overview of some approaches of CPM data content selection.

The authors of [40] have shown that redundancy can be reduced, up to 4 times, while maintaining high awareness rate for short V2X communication range, i.e. below 100m. Complementary, the authors of [43] showed up to 6.5 times of redundancy can be observed when the penetration rate of CAV is 50%. Additionally, this work introduces a redundancy control algorithm that randomly selects objects in CPM based on the transmission probability. Results show that a high awareness ratio is maintained while significantly reducing redundancy. However, such approach may be unsafe in case a critical object is not shared in the V2X network due to the random data selection process.

While current approaches seek to minimize data redundancy when sending CPMs, such redundancy can also have positive effects, for example, to improve accuracy or security [45, 46, 47]. In addition, approaches for channel load control do not take in account message content to prioritize the transmitted packets and few works considered channel load as a metric for CPM content selection.

Ref	Principle	Approach	Redundancy Control	Channel load
[35]	Periodic verification of conditions on detected object (Novelty, Distance & Speed Variation, Age)	Frequency and Dynamics-based	No	Yes, for algorithm evaluation
[37]	Vehicles equipped with sensor can extend their CAM to share characteristics ((position, speed,...) on behalf of their neighbors	Object-self announcement	No	Yes, for algorithm evaluation
[36, 40]	Consider received objects in addition to the detected objects when applying dynamics-based generation rules from [5]	Dynamics-based	Yes	No
[43]	Analyse data redundancy from Line Of Sight (LOS) model and estimation of vehicles density and objects selection from probability assignment function	Confidence & Distance	Yes	No
[44]	Anticipate the value of information, i.e. added knowledge of sharing a detected object from an ego vehicle to one of its neighbor	Entropy	No	No
[41]	Assess congestion to select between different object inclusion policies (1) include all objects, 2) include objects satisfying dynamics-based generation rules and randomly include other objects 3) include only objects selected from generation rules)	Dynamics-based with DCC	No	Yes for transmission control
This work	Context-aware CPM generation and content selection based on channel and roadside infrastructure availability	Dynamics-based	yes	yes

Table 2.2: Existing CPM data content selection approaches

## **DCC summary**

To conclude, channel congestion directly impacts vehicular networks performances, especially in the scenarios with high densities which lead to the increase of packet loss and hence degradation of packet delivery ratio and transmission delay. This is why ETSI specified DCC framework which aim to optimize communication parameters with the objective of reducing the overall channel load. However, such algorithms reduce the amount of exchanged information between vehicles leading to an eventual non-satisfaction of the requirements in terms of application reliability as well as a limitation on cooperative awareness and collective perception levels. Consequently, the communication should be extremely intelligent and aware of the overall driving environment and external factors. Hence, the communication should be context aware. In the next sections, we will focus on context awareness and its benefits to ensure an intelligent and optimized communication within all vehicular nodes (vehicles, road infrastructure, etc).

## **2.4 Context aware computing**

The concept of context awareness is not new and existed since the 90s [48]. To be able to use "context" effectively, it is essential to understand what is context and how it is used. Several works interested in the latter by defining context and context awareness [49, 50, 51, 52]. In [53], the authors divided literature on context aware systems into 2 groups. The efforts on the first group focus on concept and research for theories and algorithms to establish context-aware systems. The second group is about applications and services in the domains of web services and M-commerce and so on. According to the definition proposed in [48] 'Context is any information that can be used to characterize the situation of an entity, where an entity is a person, place, or object, that is considered relevant to any interaction between a user and an application, including the user and applications themselves'.

Context awareness emerged in the area of ubiquitous computing as the capability for a system/application to 'use context to provide relevant information and/or services to the user, where relevancy depends on the user's task' as defined by Abowd et al. in [48]. Furthermore, the authors of [54] proposed a reference framework to identify and investigate each key functionality of context-awareness applied to ubiquitous computing. Later, this concept has been inherited into different domains including mobile computing, pervasive computing and Internet of Things.

For mobile computing, several studies were developed about context awareness. For instance, the authors of [55] focused on reviewing works about context-awareness in mobile platforms. They also proposed solutions to the challenges of mobile sensing including accuracy and power consumption based on a recognition of the current context. In [56], Capurso et al. presented a survey of context awareness applied in mobile platforms confirming the potential capability to adapt application behavior for different use cases such as indoor and outdoor localization or movement tracking based on the environmental and collected contextual information. Furthermore, the authors of [4] applied machine learning techniques to design, implement and evaluate a context aware system that can learn personal user preferences/requirements (i.e. contextual data) in terms of user state and adapt its settings based on past experience.

Context is a fundamental concept in pervasive computing. In this area, computational capabilities are integrated into everyday objects so that less interaction with users is necessary, for example by relying on effective communication or by performing automated tasks. In such computing environment, context-aware systems use contextual data related to the user, any time and any place, to adapt their operations according to the environmental situation. In fact, context-aware applications are the applications that are capable to adapt their operations to the current context. The latter is provided by sensing the environmental contextual information without the need of user intervention [57]. Particularly, in [57], Baldauf et al. reviewed context, which is first derived from

observations of both external environment and internal system behavior. Then, contextual data is used to control system parameters. They also studied existing context aware systems detailing their models and their architectures. These systems take benefit from contextual data to adapt their behaviors according to user requests.

Applied to IoT field, context awareness gained a lot of attention thanks to its advantages when a huge number of sensors are deployed [58]. To reduce the information redundancy generated by different sensors, the authors of [59] proposed a context aware architecture so that relevant sensor data is automatically selected for a user based on his/her requests. This architecture allows users to obtain a high level of contextual data using reasoning techniques such as data processing and data fusion. In that area, Gite et al. [60] introduced context awareness for Multi Sensor Data Fusion (MSDF) system in IoT. Their idea is to apply an intelligence to fuse sensor data using an efficient context aware framework so that unwanted data is removed. In [61], the authors reviewed literature on smart home and confirmed that context awareness is the key solution to develop a private and secure IoT-based smart home because it allows storage and use of contextual information, and provide users with relevant services depending on their requested tasks. Targeting applications of smart home, the authors of [62] applied fuzzy logic based algorithm in the development of several smart home scenarios and showed the importance of context awareness in smart home environment where adaptive decisions should be taken based on user actions interpretation.

To summarize this part, table 2.3 lists the above-mentioned efforts made for context aware computing, the objectives, data used in building context, and the applicability of the idea to C-ITS.

Ref	Domain	Objectives of context-awareness	Data used in building context	Applicability to C-ITS
[54], [48]	Ubiquitous computing	Adapt system (e.g phone) behavior (e.g accept or reject a call) according to the user preferences	Location, time, user identity, user current activity and etc	Adapting vehicular communication system behavior based on collected contextual data.
[57]	Pervasive computing	Improve application operations based on user requests	External environment and internal system behavior and etc	Vehicular communication should be made and optimised by taking into account the external environment of the vehicles such as road layout, traffic condition, weather condition, roadside infrastructure availability and etc.
[55], [56], [4]	Mobile computing	Change user behavior based on the environment and collected contextual information	Location, number of users and etc	C-ITS application requirements should be considered as a context.
[59], [60], [62]	IoT	Take intelligent decisions according to users requests and improve system performance in terms of response time and accuracy	Sensor data	Data redundancy management and processing can be applied to C-ITS

Table 2.3: State of the art of context awareness



## 2.5 Context aware communication for ITS

Driving is a complex task as it requires several continuous interactions between the driver, the vehicle and the environment [63]. Thus, intelligence, i.e. context-awareness is essential such that the vehicle can drive safely and efficiently [64]. Applied to the domain of vehicular networks, several definitions of context were proposed. Sepulcre et al. [65] defined a context as "collection of measured, exchanged and inferred knowledge that characterizes the vehicular environment and the communication needs and conditions of a vehicular node". Although several proposals were developed in the literature, there seems to be no exact definition that characterises context and no consensus exists so far on context types. For instance, in [66], context for vehicular networks could be categorized into 4 types : 1) local, 2) external, 3) general-related to transportation, and 4) general-unrelated to transportation. The local category includes mobility information of the vehicle such as location, speed, acceleration and etc. The external category includes mobility information about other vehicles. The general-related to transportation category contains traffic and parking information. Finally, the general-unrelated to transportation category contains for example weather conditions. From another point of view, the authors of [64] characterised context types to 4 categories : 1) the operating environment of the vehicle and all relevant objects within it, 2) the driver, 3) the vehicle with the built-in Driver Assistance System and 4) national traffic regulations. In general, in ITS domain, context is any information that describes the driving and environment situation and that can be used to modify intelligently system behavior depending on application requests.

Context awareness attracted great interest in vehicular networks since it allows vehicular nodes to share contextual data including safety and non safety information collected through sensors and vehicle communication capabilities in order to improve system performance. From one hand, this contextual information tends to change dynamically,

and hence context aware systems should be always adapted to environmental and non-environmental conditions in order to be capable of adapting their parameters and behaviors. Also, they should be able to model the context, process it and control information to be adapted to the current context [67]. From the other hand, in such systems, context aware communication should integrate context awareness on communication processing and data management including communication protocols and parameters control, so that optimised communication and intelligent system behavior are ensured.

The authors of [66] reviewed previous work related to context aware application of vehicular networks and classify them in three categories based on their main efforts: environment (urban, rural, highway,etc), system and application (service type, system architecture, communication type, and application action pattern), and context-awareness. In particular, in the works of context awareness category, the authors focus on context types and context gathering method parameters.

To better understand the existing context aware systems, we classify them to 3 main categories depending on the objective: context aware systems for road safety, context aware systems for V2X communication optimization and finally context aware systems for security aspects especially misbehavior detection. The second category could be further divided to 2 sub classes: resource control and communication profile selection.

In the first category, i.e. road safety, the majority of the existing works target either CAS [68, 69, 70, 63] that allows connected vehicles inform their presence to the surrounding entities or CPS [65, 71, 36] which allows vehicles or roadside units to inform about detected objects by their local sensors. Since human error is the first cause leading to road accidents, different works are interested in studying driver behavior especially abnormal behaviors and drowsiness. In particular, in [72], a context aware driver behavior detection system is developed in order to warn other drivers on the road for possible accidents using CAMs. Contextual data about the vehicle, driver and environment is used to infer different driver behaviors including normal, drunk, reckless and fatigue

status.

For the second category, i.e. V2X communication optimization, main efforts dealt with either resource control such as radio resource control or communication profile selection. For resource control, as road safety relies on the frequent exchange of messages, researchers interested in optimising CAS communication parameters in order to ensure message transmission reliability. In [25], a context aware adaptive beaconing system is presented. It allows the dynamic transmission of CAMs based on channel load status and danger severity between vehicles. Also, in [73] the authors used different contextual information in terms of connection-dependency, communication type (unicast or broadcast), and packet payload size to select edge nodes that are responsible for routing decision. They applied a fuzzy logic-based algorithm which allows to find the best routing edge nodes for packet forwarding while ensuring an efficient use of wireless resources.

From the other hand, in heterogeneous networks, different wireless communication technologies co-exist and could be used for ITS services. Thus, the adequate selection of communication technology and its parameter is very important to enhance system performance and optimise service cost. In this context, Sepulcre and Gozalvez, [74, 65] proposed a novel context-aware heterogeneous V2I communications technique that exploits context information (communication metrics, mobile state and user preferences) to make intelligent decisions on the most adequate communications technology to use. The decision is directly made by each vehicle with assistance from the infrastructure. Such a system allows to improve both individual and system performance as well as reduce the economic cost of C-ITS service.

Finally, as exchanged information is crucial for security purposes and sharing falsified mobility information may disrupt any C-ITS application, it is essential to study security issues and propose some solutions [75]. Targeting this challenging category, Ghaleb et al. [76, 77] worked on a context aware scheme that aims to detect misbehavior and classify CAMs into correct or false messages. Context awareness confirmed its effectiveness since

the results of the proposed scheme showed a 73% reduction in false Alarm rate and a 37% improvement in the detection rate compared to a non context-aware scheme results. To summarise this state of art section and show the previously mentioned categories, Table 2.4 details the use case, used context and the benefits of using context awareness for each paper.

In conclusion, context awareness should be used to control/adjust communication parameters such as message generation rate, message content, message size, networking protocol selection, and etc in order to ensure an intelligent and optimised exchange of information between vehicular entities as well as an improvement on the overall system performances. In the next section, we will focus on the context types used on the literature.

## **2.6 Context types for road safety applications**

Based on our literature study, we observe that existing efforts considered several contexts to build context awareness for C-ITS. Thus, we propose to classify them to 3 main categories 1) resource availability, 2) application requirement, and 3) environmental factors.

### **2.6.1 Resource availability : DCC mechanism**

Vehicular communication is based on information exchange between vehicular nodes based on different services including Cooperative Awareness Service (CAS) and Collective Perception Service (CPS). As the transmission reliability of messages is of great importance in ITS, several algorithms have been proposed to control radio resources by adapting some communication parameters such as CAM transmission rate [25, 26] and CAM transmission power [68]. In communication systems, it is not new to take into account radio resource availability. Indeed, DCC algorithms including Reactive DCC [80], [81] and Adaptive DCC [80] have been proposed to control facilities layer message generation rate, packet forwarding parameters, communication parameters such as trans-

Ref	Application/use case	Used contextual information	Context awareness benefits
[72]	Abnormal driver behavior detection	internal (vehicle's speed, acceleration, the direction of driver's eyes, position in lane, the level of alcohol in the driver, blood) and external (traffic, weather and road conditions)	Improve Road safety/Reduce accidents: disseminating warning messages that include corrective actions for other vehicles on the road
[73]	Radio resource optimisation	connection-dependency (connection-dependent or connection-independent), communication type (unicast or broadcast) and packet payload size	Edge node routing selection to improve system performance in terms of resource utilisation
[25, 26, 68]	Communication parameters optimisation	Vehicle's velocity, inter-distance vehicle, traffic density, danger severity, channel load	Improve road safety by adapting message rate/power for each traffic situation
[65], [74], [78]	Communication mode/profile selection	Available technologies , technology cost	Improve system performance while reducing economic costs
[76, 77]	Misbehaviour detection	Vehicle position and neighbor vehicles information	Improve system security, dynamic detection of suspicious messages and reduction of false Alarms
[79]	Driving assistance system for autonomous vehicle	Vehicle type, road type, road condition, weather information	Enhance autonomous vehicles and self-driving

Table 2.4: State of the art of context awareness in ITS

mission power and modulation rate and etc. [32, 23, 82, 27]. Besides, most of the existing works on communication control have been dedicated to IEEE 802. 11p. Here, channel busy ratio (CBR) and Channel Busy Time (CBT) have been used by these algorithms as the main metric to express the current channel load and to assess how communication parameters should be adapted. In [27], the authors evaluated the communication performances targeting CA service of reactive DCC and compared the results to the case without DCC. They showed that up to 60% of improvement can be obtained in terms of packet delivery by reducing message generation frequency. Since connected and autonomous vehicles will be based on multiple heterogeneous V2X services (CAS, CPS, DENS and etc), the authors of [83] worked on the integration of a Facilities-layer DCC which allows handling different V2X services. As for CPM dissemination, several works interested in studying redundancy mitigation techniques that aim to adapt CPM generation rules based on channel status [35, 36, 40]. More recently, the authors of [84] proposed a congestion control policy for collective perception service. The latter control the frequency of transmission of CPMs containing detected objects based on their relative positions among neighboring vehicle

Despite its capability to effectively reduce channel congestion, DCC does not consider its impacts on the road safety applications, more precisely it is not clear if the performances are meeting the application requirements. In addition, DCC can have negative effects on awareness level and latency of cooperative perception [85]. Besides, DCC mechanisms as well as redundancy mitigation techniques do not consider messages content, thus, they cannot establish a priority between messages, for example, to favor a CPM that contains an occluded vehicle over a CPM with already detected vehicles.

## 2.6.2 Application requirement

Using vehicular networks allows the deployment of several C-ITS applications, especially safety applications, the first motivation of ITS, that aim to reduce fatalities and avoid

road accidents. Safety applications gained a lot of attention since they are considered as the key solution to allow the exchange of local as well as perceived information. Local information presents the self knowledge so-called "awareness" of each vehicular node such as position, speed, direction and so on. Perceived information consists on the information (position, speed, orientation, etc) related to the surrounding entities perceived by local sensors. The exchange of such mobility data requires real time constraints and strict requirements for safety applications: very short delay and high reliability for information reception [86, 87]. For instance, some safety applications such as Cooperative Forward Collision Warning need to exchange periodic messages with a transmission rate between 1Hz and 10Hz and are sensitive to packet loss, thus requiring a high level of reliability and low latency. Consequently, it is of a main importance for vehicular nodes to be informed in time about an eventual accident before its occurrence. In contrast, passengers can tolerate to receive a video/audio downloaded from Internet with a certain delay for infotainment applications. Focusing on safety applications, ETSI have specified functional and operational requirements related to Road Hazard Signalling (RHS) application [88] as well as Longitudinal Collision Risk Warning (LCRW) application [89] based on CA and DEN services for both originating and receiving modes.

In [90] Sepulcre et al. proposed and evaluated an integrated congestion and awareness control protocol called INTERN for CA service. It aims to adapt dynamically the transmission parameters (transmission frequency, transmission power) taking into account the vehicle's application requirements and the experienced channel load. The application requirement is specified as a minimum number of messages are correctly received per second by all vehicles within a given warning distance. In the same context, the authors of [91] proposed a contextual cooperative congestion control policy for lane change assistance application based on CA service that aim to reduce communication channel load using the traffic context information of each vehicular node while ensuring a minimum level of application reliability. In fact, they considered the minimum warning distance between

vehicles to avoid accidents and fixed the minimum required reliability to 99.9999%. We believe that application requirement in terms of communication metrics, for example PDR or delay, should be contextualised, i.e. varied based on the vehicle's or traffic situation.

### 2.6.3 Environmental factors

Besides to resource availability and application requirements, several works considered environmental factors as contexts to build context awareness for C-ITS. In fact, these external factors are of prime importance to make system control decision since they impact the overall communication system behavior. They consist on different external information that could be collected from driving environment including mobility information of neighbouring entities, traffic conditions (density and pattern), road layout, available services, weather conditions and etc. In [72], the authors worked on detecting abnormal driver behaviors and considered weather condition parameters such as temperature as external factors that impact driver behavior and road safety. As for collective perception, the authors of [39] showed that local perception drops quickly with the increase in traffic density due to limitation of vehicles' field of view and blockage effects of surrounding vehicles. Thus, it is essential to consider environmental condition in terms of traffic density in order to gain more information about road environment. In addition, Wang et al. [38] proposed a roadside units deployment strategy in order to maximize object coverage. They confirmed that carefully deployed road side infrastructure help to allow better coverage of roads as well as better vehicle environment sensing. However, in this work communication aspects are not considered, and it is not clear if I2V communication will be beneficial for collective perception. Hence, we are interested in studying the role of I2V communication for CPM dissemination, particularly when roadside units are available in the environment. In other words, we intend to study the benefits of considering the presence and availability of roadside infrastructure, which is our environmental con-



text, for collective perception service especially when roadside infrastructure is installed in such a way that it has higher communication and perception coverage than vehicles.

## **Discussion**

From our literature review on context awareness for C-ITS, we observe that there is no work that considered the above mentioned 3 contexts (resource availability, application requirement and environmental condition) at the same time and we believe that combining multiple contexts could provide higher performances for application requirement satisfaction and communication system optimization. Motivated by this, we focus on context awareness in collective perception targeting collision avoidance applications using V2V and I2V communications. In other words, we intend to ensure V2V/I2V performances meet road safety application requirements. Consequently, first, we should define application requirements in a comprehensive manner to communication systems. Then, since channel congestion is a critical issue, we consider resource availability as a context that should be taken into account when communication parameters would be adjusted. After that, we study road side infrastructure communication impacts on message dissemination, that shows the benefits of switching I2V and V2V communication when a RSU is available in the environment. Finally, once requirements are defined, benefits of RSU on message dissemination are known and resource availability is considered, communication parameters to control CAM and CPM dissemination are identified : message generation rate and content selection.

## **2.7 Conclusion**

In this chapter, we first reviewed C-ITS applications and services and reported different standardisation activities on facilities layer particularly CA, CP, DEN services definition and their message generation rules. We also put a focus on DCC framework as the solu-

tion to avoid performance degradation by reducing the amount of exchanged information between vehicular nodes and adapting resource utilization. The DCC resource optimization limits cooperative awareness and hence communication control requires to consider other factors, i.e. contexts in order to ensure an efficient channel load management and application requirement satisfaction.

The second part was dedicated to review different works about context awareness applied to several domains particularly ITS. In the latter, context aware systems showed their effectiveness for several challenges including road safety applications, communication profile optimization and security issues. In particular, for road safety applications, researchers interested in message dissemination optimisation based on contextual data in terms of channel load status or environmental factors while respecting application requirements. The majority of these efforts used a single context type to control communication and lacks from much more intelligent algorithms that take into account multiple contexts to adapt communication parameters. In the next chapter, we present the contexts that will be considered in this work and establish our analytical models to study the potential benefits of context aware communication for road safety applications.

# Chapter 3

## Analysis of context aware communication for collision avoidance applications

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## 3.1 Introduction

In this chapter, we focus on two main parts. In the first part, we identify context aware architecture focusing on the management layer which implements context awareness in 3 phases: context acquisition, context reasoning and system control. Then, we define contexts that we believe are the most important to impact safety applications. The latter are proposed to support communication parameters control for collision avoidance applications. The second part concerns the proposition of analytical models to build context awareness for road safety. Particularly, we model collision avoidance application requirements as well as the benefits of using road infrastructure (I2V communication) for collective perception.

## 3.2 Context aware system architecture

### 3.2.1 Context aware architecture for ITS

In our opinion, the management layer is a natural placeholder for context-awareness since its objective is the optimisation of communication system and its behavior. Indeed, in [92], the authors proposed an architecture in which the management layer implements context awareness through the following three phases as depicted in Fig. 3.1:

- *Context acquisition*, which consists on collecting data from different sources including communication protocols and sensors.
- *Context reasoning*, which aims to employ intelligent techniques in order to establish a context. This phase presents the transformation of collected data from context acquisition phase to information that could be known and processed by system control module regardless of the acquisition sources and/or methods.
- *System control*, which acts on the communication protocols and modules as a re-

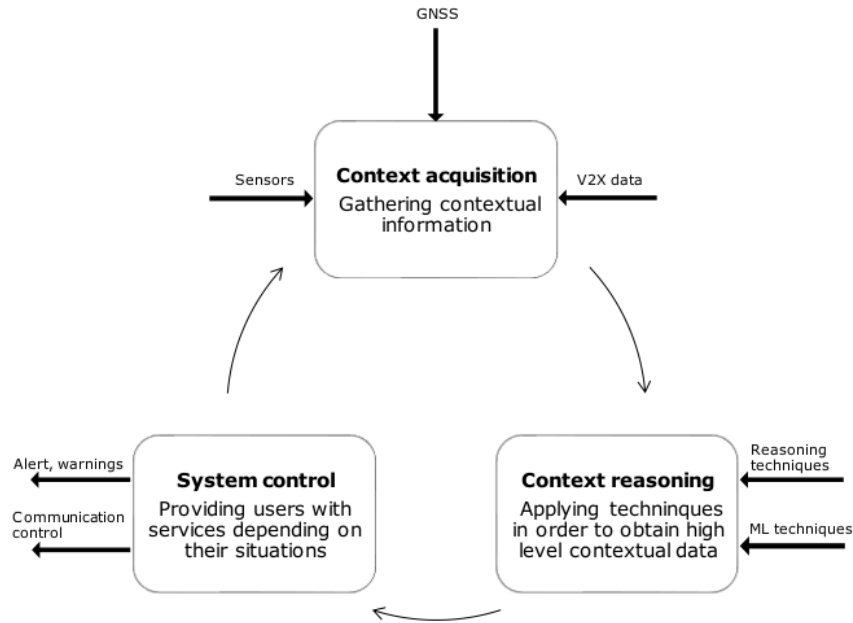


Figure 3.1: Context cycle

response to the context established in the context reasoning phase. Multiple parameters of the different layers/protocols could be controlled in this phase including technology selection, message generation rate control, power control, data rate control and so on.

As explained above, for context-aware communication, the management layer interacts with other layers particularly during the context acquisition and the system control phases (see Fig. 3.2) over the already-defined interfaces: MI (Management Access) interface, MN (Management Network) interface, MF (Management Facilities) interface and MA (Management Applications) interface [93]. The followings are the examples of such interactions.

1. Access layer information e.g., on link availability and radio channel conditions are collected and sent to the context aware system via the MI interface. The latter sends back instructions regarding the appropriate technologies, channels, transmission

power, etc for the target applications and data flow.

2. Information on e.g., routing are retrieved from network layer via MN interface. The management layer can specify the adequate address type (IP or geonetworking) and routing protocols.
3. Information on e.g., the number of neighbors, their positions and road event can be retrieved from the LDM. The management control may configure message generation frequency, message size, message fragmentation and etc.
4. The status of the applications and their requirements can be retrieved from the application layer via the MA interface. The management layer may later adjust application parameters including the message content, message size, and etc.

It should also be noted that for context acquisition, the management layer may obtain information from other sources such as sensors, cloud/edge servers, and so on. As for cooperative awareness and collective perception services, the management layer shall be able to control (or request to control) CAM/CPM transmission parameters based on context recognition.

Table 3.1 details the potential collected parameters in each layer during context acquisition phase and the parameters that could be optimised during system control phase.

In this work, targeting collision avoidance applications, we focus on facilities layer particularly CA and CP services. The next section will detail different contexts that we believe crucial for achieving such a goal.

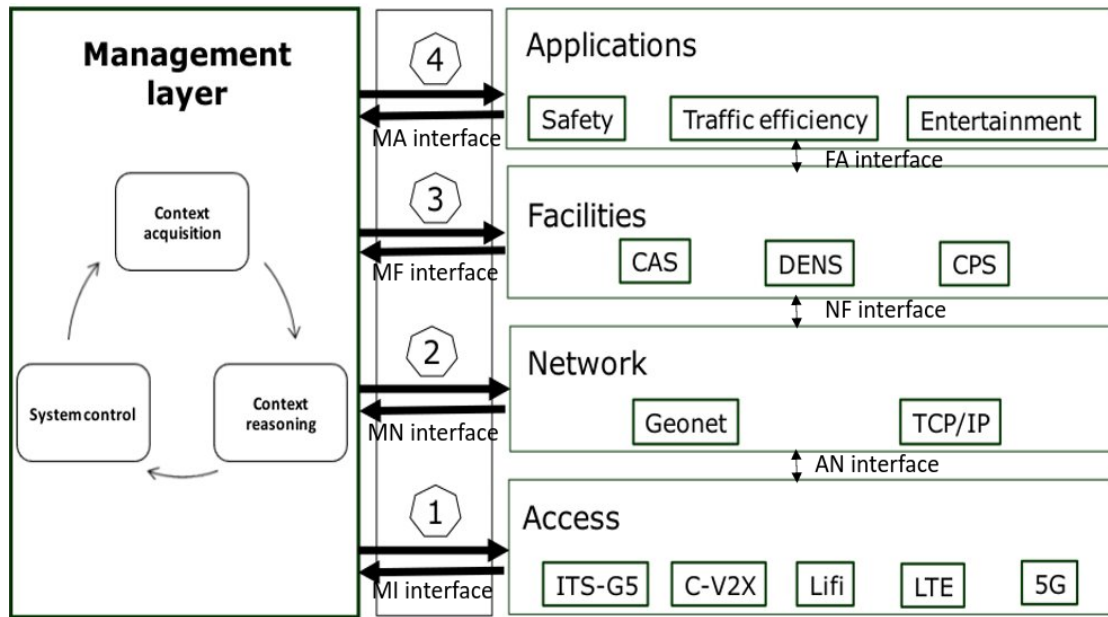


Figure 3.2: Context-aware system architecture

### 3.3 Context identification

#### 3.3.1 Collision avoidance applications

Regardless the advancements in vehicle technology, the number of road accidents is still high [94], which needs innovative solutions for collision avoidance systems and intelligent road infrastructure. To this end, road safety applications aim to extend perception of road users by informing or alerting of oncoming vehicles, pedestrians or presence of objects or road hazards. The most known examples of services/applications in this category are collision avoidance, road condition warnings, lane change assistance.

#### 3.3.2 Contexts identification for collision avoidance applications

Although various types of contexts can be imagined, for collision avoidance applications, we believe that at least applications' requirements, radio resource availability, and environmental context, shall be considered as illustrated in Fig. 3.3. A high level illustration



Layer	Context acquisition parameters	System control
Access	<b>Wireless technologies</b> that can be used in the current C-ITS station (C-ITS-S), the <b>link quality</b> between the current C-ITS-S and its neighbors and <b>channel occupancy</b> for a given technology.	Technology and channel selection
Network & Transport	<b>Routing information</b> particularly protocol type and parameters and the <b>addressing scheme</b> .	Network protocol selection and parameters tuning
Facilities	<b>Message size</b> and <b>message generation rate</b> of different facilities servers	Configuration/adaptation of message generation rate, message size optimisation, message fragmentation, data exchange management
Application	Application requirements which can be <b>latency</b> , <b>throughput</b> , <b>PDR</b> , and <b>PIR</b>	Data content

Table 3.1: Parameters for context aware system architecture

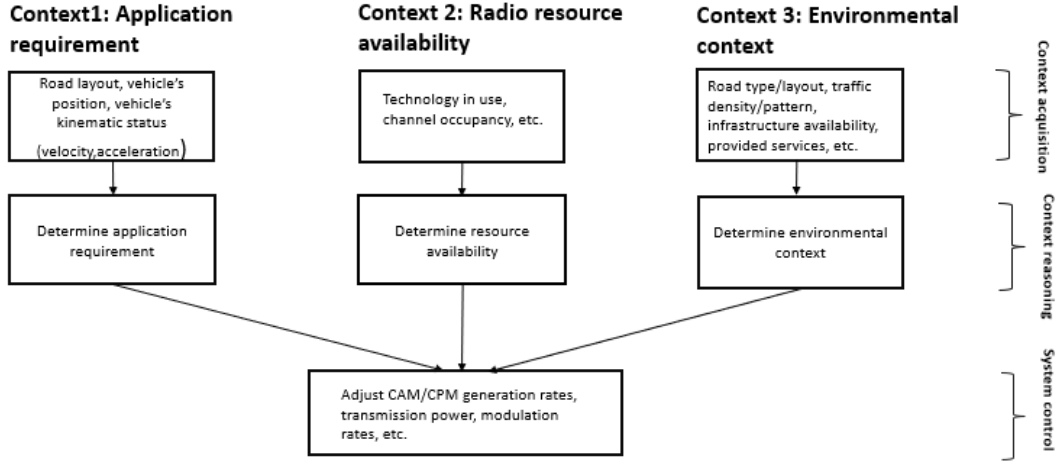


Figure 3.3: Context awareness for collision avoidance applications

of context aware architecture for communication profile adaptation for road safety applications is described in Fig. 3.4. The figure shows the interaction of management layer with application, facilities and access layers. In particular management layer is composed of two modules: Application requirement assessment module and the commu-

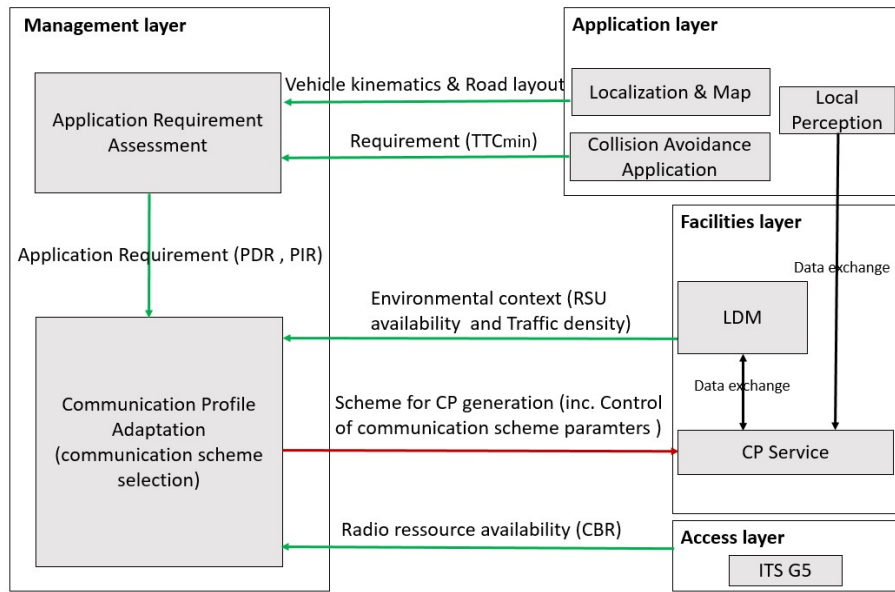


Figure 3.4: Communication profile adaptation for collective perception service

nication profile adaptation. Here, the green arrows represent context acquisition and the red arrow represents system control.

In the context acquisition phase, the communication profile adaptation module collect information (green arrows in Fig. 3.4) as described below.

- From the application layer, it will collect information on vehicle kinematics, road layout (from localization and Map module), and the requirements of the collision avoidance application e.g., in terms of time to collision (TTC). Then, communication requirements in terms of PDR and PIR can be calculated and used as a context by communication profile adaptation module.
- From the facilities layer, particularly from LDM module, the communication profile adaptation module retrieves not only number of neighbors but also environmental context, i.e. presence and availability of RSUs.
- From the access layer, the intelligent module search for the technologies in use (e.g.

ITS G5) and radio resource availability via e.g., the CBR metric.

In the reasoning phase, the communication profile adaptation module evaluates target communication performances and checks if the application requirements are met. Finally, this intelligent module use contextual data collected from different layers to make decision about the most adequate communication parameters. For example it can request the CP service to adapt the CPM generation rate and contents to be included in each CPM (red arrow).

### **Application requirement**

We believe that, communication systems have to be aware of the application requirements and be able to self-adapt in order to meet these requirements. This is especially important for C-ITS because the applications are extremely critical and hence, the traditional best-effort approach shall be avoided. Unfortunately, the current V2X communication systems do not really control their parameters by taking into account the application requirements. In fact, the application requirements are not clear, as it depends on the current traffic and vehicle situations. Moreover, the requirement of collision avoidance applications are often not comprehensible for the communication systems, because the domains use different metrics (e.g., TTC vs. PDR/PIR). Our objective is hence to build context in terms of application requirement that is comprehensible for the communication systems.

To build context in terms of application requirement, in the acquisition phase, the system needs to collect information about particularly the ego-vehicle's position, its kinematic status (velocity, acceleration, heading and etc), the layout of the road on which the vehicle is driving, and other information such as the presence of the surrounding 3D objects. Note that, as it is about collision avoidance, one may imagine further information such as vehicle characteristics (braking power etc.), tire condition, weather condition, and

pavement condition. However, since CAS and CPS are to avoid collision while TTC is greater than e.g., 3 seconds [88], we can ignore those information. In the context reasoning phase, the system needs to estimate the target communication performances based on the collected information about vehicle kinematic, road topology and application requirements in terms of TTC. Such an estimation is essential to check if communication system performance is meeting application requirement, in particular regarding the application reliability. If such requirements cannot be met, then, communication parameters should be adapted in order to reach the target performances.

As mentioned earlier, since communication performance is generally assessed using communication metrics such as PDR and PIR, application requirement should be expressed by the same metrics in order to be evaluated against performances. In this work, we intend to express such requirements based on an estimated collision risk between vehicles, which will be the focus of the next sections.

### **Radio resource availability**

In vehicular ad hoc networks, technologies like IEEE 802.11p or LTE-V2X are used and the vehicular nodes compete against each other in order to acquire radio resource for their transmissions. Because there is no central system allocating radio resource to individual nodes, such a network is vulnerable to channel congestion problem, which happens when too many nodes compete for the radio resource and simultaneously access to the channel, leading to packet collisions. In such a situation, the radio resource can be completely wasted for packet collisions, leading to extremely poor communication performance. It is hence very important to optimise the resource utilisation by establishing context in terms of radio resource availability.

Building context in terms of radio resource availability is somehow similar to what distributed congestion control (DCC) algorithms do. Indeed, multiple DCC algorithms have been proposed to control facilities layer message generation rate, packet forwarding

parameters, transmission power and modulation rate and etc. [32], [23], [82], [27]. In general, they first measure CBR (context acquisition), compare it to the optimal operational point of the used technology, which is around 60-70% for IEEE 802.11p (context reasoning) and finally control communication parameters e.g., CAM/CPM generation frequency (system control). In this work, we are interested in collecting (context acquisition phase) contextual information in terms of channel occupancy, comparing it to a threshold (context reasoning) and finally controlling message generation rate and message content (system control phase) while ensuring channel occupancy optimisation applying intelligent context-aware algorithms detailed in chapter 4.

### **Environmental context**

Besides to application requirement and radio resource availability contexts, external contexts, e.g. context related to the environment, should be taken into account. In fact, environmental factors such as road layout, road infrastructure, traffic density, traffic rules, and so on may impact the choice of the transmitting vehicular node (vehicle, RSU, mobile edge computing (MEC) device, base station, etc) as well as the rate of message transmission. Consequently, such context plays an important role in the effective deployment of road safety applications and improvement of system performance.

In this thesis, we focus on the presence of roadside communication infrastructure e.g., RSU and/or MEC devices that are equipped with sensors. Indeed, although both vehicles and RSUs can contribute to CPS, they have very different characteristics in terms of sensor field of view, communication coverage, and processing capacity that favor RSUs over vehicles. Therefore, we are interested in context-aware communication that considers the environmental context particularly the number of available RSU and their characteristics such as positions, field of view, communication coverage, etc.

## 3.4 Modeling contextual information supporting collision avoidance applications

### 3.4.1 Building application requirement

In context-aware communication, a context is first derived from observations of both external environment and internal system behavior, and then, used to control system parameters, i.e. the communication parameters. Hence, understanding the relationship between context and the target communication parameters becomes extremely important. As for collision avoidance application, on the one hand, an estimation of collision risk between vehicles can be modeled via various metrics including collision probability [95] and Time To Collision (TTC) [86]. On the other hand, performance of the communication system is usually assessed using communication metrics [96] such as Packet Delivery Ratio (PDR), latency, throughput or packet inter-reception time [97]. Consequently, linking metrics between these two categories is crucial for context-aware communication targeting collision avoidance applications, and it is addressed in this work. This section is dedicated to model contextual information for application requirement definition.

#### Possible collision scenarios

In this section, we elaborate a comparative study about possible collision scenarios showing for each configuration the potential point of crash. One may imagine several scenarios that potentially lead to collisions between vehicles. In Fig. 3.5, we depict 4 possible collision scenarios and show potential crash point  $P_{crash}$ :

- First, (a) configuration consist on a multi-road highway where a car-following model is provided. A collision may occur when the blue car brake suddenly in such a way the orange car does not have enough time to fully stop (we suggest that standard time to stop a vehicle is 2 seconds). To avoid the collision, orange vehicle should

gather fresh and updated data about blue vehicle (velocity, acceleration and so on) and must respect safety distance separating it from in front vehicle.

- The second, (b) configuration shows an intersection model where two vehicles may collide in the center of the road. In this case, in order to avoid the potential accident, depending on collected information about blue car velocity, orientation, position and etc, orange car should adjust its kinematic parameters including its velocity and acceleration.
- The third, (c) configuration describes a lane changing scenario which consists on a 2-road highway allowing orange vehicle to change its current lane. If the latter is not aware of the presence of the blue vehicle running at adjacent lane, a collision may happen. Here, recent and updated contextual information about the vehicles' velocity, acceleration, position, orientation and etc, shall be collected and exchanged between the vehicles to avoid such a situation.
- Finally, (d) configuration presents occluded pedestrians (by a parked bus) who may jump into the road. Orange car can not perceive pedestrians by its local sensors since they are in Non Line of Sight (NLOS) conditions. Consequently, to avoid the collision, it has to collect contextual information from neighboring entities that could detect pedestrians (e.g. red car) about position and distance to the vulnerable road users.

From the above configurations, it can be understood that given the road layout, dynamics and near future trajectory of an ego vehicle, and safety requirements (e.g. minimum time to stop a vehicle), collision points, i.e. location where accidents have an important potential to occur, could be known. Then, starting from such collision points, we intend to develop application requirements for collision avoidance scenarios as presented in the next sections.

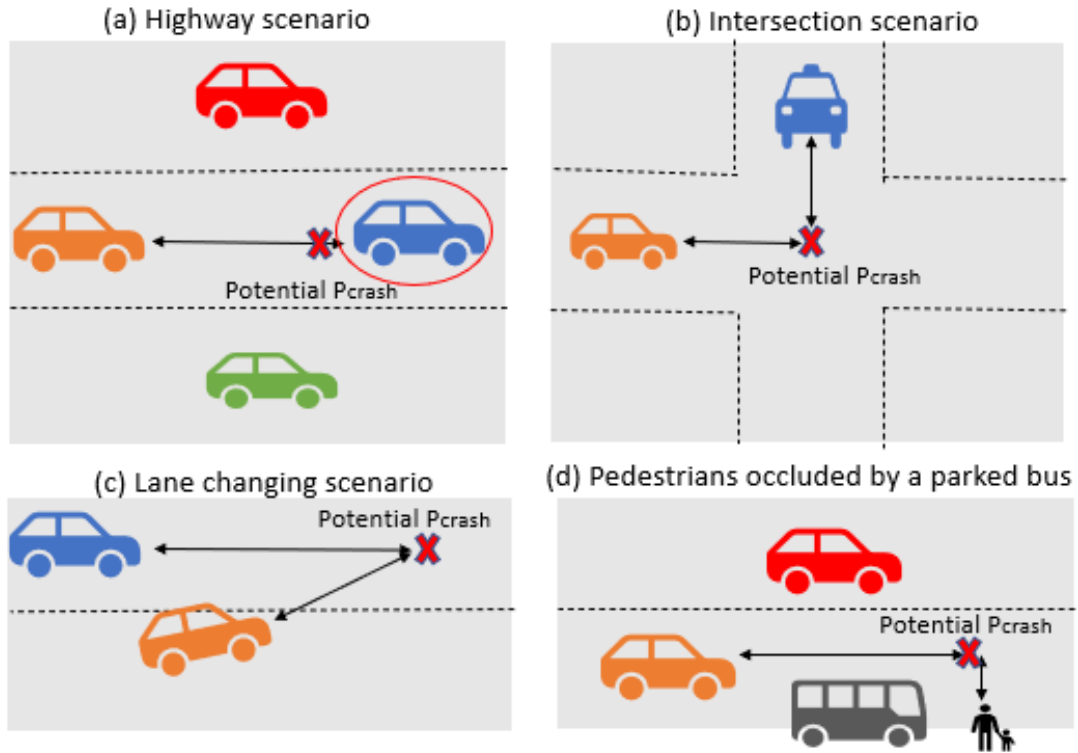


Figure 3.5: Possible collision scenarios

### Target collision avoidance scenario

Let us imagine the scenario illustrated in Fig. 3.6, where two vehicles are approaching a junction point  $P_{crash}$ . Such a scenario could be derived from the above-mentioned configurations, e.g. lane changing or intersection scenarios. In order to avoid collision, the vehicles need to know the presence of each other via CAMs and/or CPMs. The message shall be received and processed early enough so that the vehicle(s) has enough time to fully stop before reaching  $P_{crash}$ . The time necessary to stop a vehicle ( $TTS$ : time to stop, see Fig. 3.6) includes driver reaction time (or computer reaction time in a case of automated cars), brake lag, and braking time; and it takes a value between 1 and 3 seconds [88]. On the other hand, collision avoidance applications (e.g., road hazard signaling and collision risk warning) will not use CAMs/CPMs, which are received too



early. According to [88], applications would use the messages received within the interval  $TTI$  (time to inform), which starts at e.g., 30 seconds before and terminates at  $TTS$  before the crash time (see Fig. 3.6).

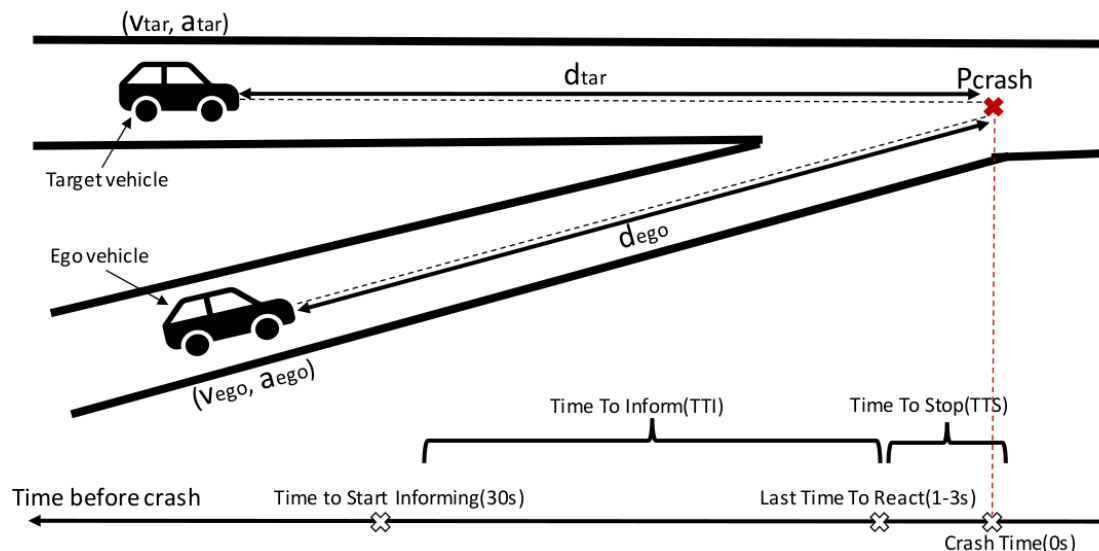


Figure 3.6: Collision avoidance scenario: to avoid an accident, the ego vehicle shall be informed of the presence of the target vehicle via CAM/CPM during TTI.

The aim of defining application requirement is to appropriately control communication parameters such that the drivers/vehicles are alerted during  $TTI$  if a collision risk is detected. Obviously, the application is, first of all, to know about the presences of other vehicles, and hence, the application requirement has to be defined based on only the ego-vehicle's information and environmental information such as road layout.

In the next sections, we propose a definition of the requirement of V2V collision avoidance application. We first model the collision probability of a vehicle approaching to an intersection. Since collision probability cannot be directly exploited by a communication system, we then propose to convert this collision probability first to the minimum PDR and then to PIR.

## Collision Probability

In this section, we formulate collision probability for an ego-vehicle with any target vehicle that has trajectory crossing with that of the ego-vehicle (see Fig. 3.6).

For a given pair of ego and a target vehicle, the collision probability is expressed as follows [95].

$$P_C = \frac{1}{(a_{\max} - a_{\min})^2} \int_{a_{\min}}^{a_{\max}} \int_{a_{\min}}^{a_{\max}} \text{coll} \left( \begin{bmatrix} a_{ego} \\ v_{ego} \\ d_{ego} \end{bmatrix}, \begin{bmatrix} a_{tar} \\ v_{tar} \\ d_{tar} \end{bmatrix} \right) da_{ego} da_{tar} \quad (3.1)$$

$$\text{coll} \left( \begin{bmatrix} a_{ego} \\ v_{ego} \\ d_{ego} \end{bmatrix}, \begin{bmatrix} a_{tar} \\ v_{tar} \\ d_{tar} \end{bmatrix} \right) = \begin{cases} 1 & \text{if there is a collision} \\ 0 & \text{otherwise} \end{cases} \quad (3.2)$$

Here,  $d_{ego}$ ,  $v_{ego}$ ,  $a_{ego}$  (resp.  $d_{tar}$ ,  $v_{tar}$ , and  $a_{tar}$ ) are the distance from the intersection, the velocity, the acceleration of the ego-vehicle (resp. the target vehicle), with a condition that  $v_{ego}$  (resp.  $v_{tar}$ ) cannot exceed a given speed limit  $V_{max}$ . Equation (1) calculates the collision probability between the vehicles by taking into account all possible variations of  $a_{ego}$  and  $a_{tar}$  within the range of maximum deceleration  $a_{min}$  and maximum acceleration  $a_{max}$ . It should be noted that  $a_{min}$  and  $a_{max}$  depend on the actual values of the velocities (e.g.,  $a_{max} = 0$  when  $v_{ego} = V_{max}$ ) and bounded by extreme values, which are determined by the vehicle's dynamics model (e.g.,  $a_{min} \geq -9.5 \text{ m/s}^2$  and  $a_{max} \leq 2.1 \text{ m/s}^2$ ).

In order to determine the application requirement for a given ego-vehicle, we shall consider the worst case, where the collision probability is maximized. This leads us to search  $V_{tar}$  and  $d_{tar}$  that maximises  $P_C$ . We have found, as one may imagine, that a higher  $V_{tar}$  leads to a higher  $P_C$ . In other words, for any ego-vehicle, we obtain the highest  $P_C$  when  $V_{tar}$  is equal to  $V_{max}$ . We now search  $d_{tar}$  that maximizes  $P_C$  when  $V_{tar} = V_{max}$ . Fig. 3.7 shows the collision probability for varying  $d_{tar}$ , for different values of  $V_{ego}$ . Here,

$d_{ego}$  is fixed to 100 m and  $V_{max} = 130Km/h$ . The results clearly show that for a given combination of  $V_{ego}$  and  $d_{ego}$ , it exists  $d_{tar}$  where  $P_C$  is maximized.

Furthermore, this  $d_{tar}$ , where  $P_C$  is maximized (see equation 3.3 ), can be calculated using an optimization tool such as Gradient Descent for different values of  $V_{ego}$  and  $d_{ego}$ .

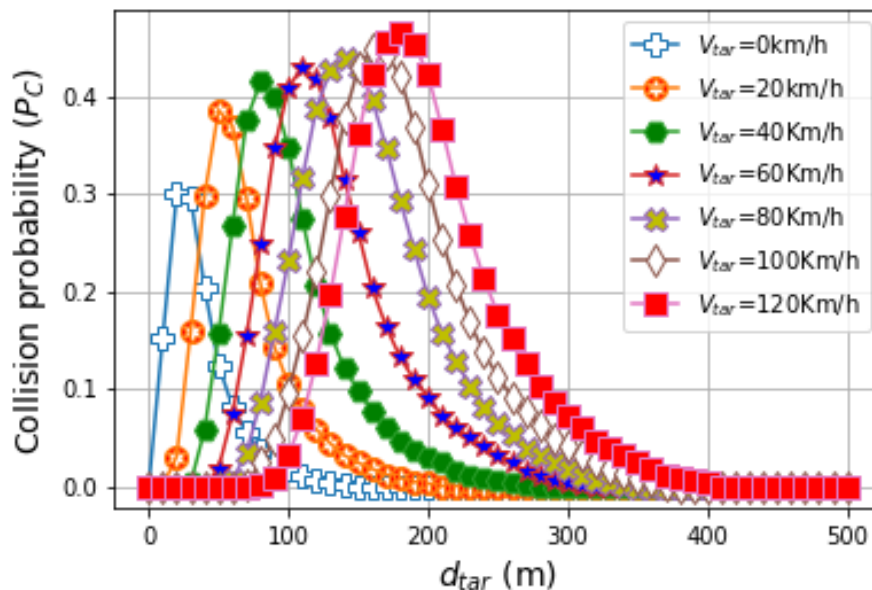


Figure 3.7: Collision probability function of  $d_{tar}$ . Here  $d_{ego}=100m$

Finally, Fig. 3.8 shows the maximum collision probability for varying  $d_{ego}$  for different values of  $V_{ego}$ .

$$P_C^{max}(d_{ego}, V_{ego}) = \max_{d_{tar}, V_{max}} P_C \quad (3.3)$$

### 3.4.2 Application requirement definition

Targeting collision avoidance, we propose to define application requirement in terms of both PDR and PIR. On the one hand, PDR is defined as, for each transmitter and receiver, the ratio between the number of successfully received messages and the total number of transmitted messages. This evaluation metric is very important as it reveals

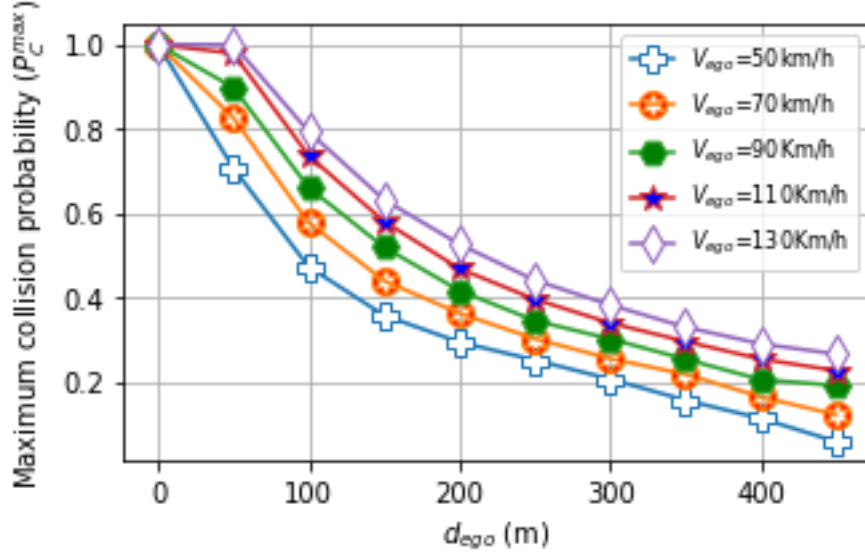


Figure 3.8: Collision probability function of  $d_{ego}$

also the percentage of packet loss and hence an overview about connectivity status between vehicles and system performance.

On the other hand, PIR is defined as the interval of time elapsed between two successful message reception. It is proposed in [98] as a critical metric that describes the level of 'situation-awareness' and that may be more accurate than PDR. Indeed, PIR enables delivery of a finer grained information and shows the message reception pattern in order to identify blackout periods where no message is received. Such a metric is very beneficial for collision avoidance applications where dangerous situations such as highway intersection may be avoided [99].

### Application requirement in terms of PDR

First, we propose to define the application requirement in terms of the minimum required packed delivery ratio ( $PDR_{req}$ , in other terms, the minimum required packet reception probability) as follows:

$$PDR_{req} = P_C^{max}(d_{ego} - d_{TTS}, V_{ego}) \quad (3.4)$$

As it is shown, the minimum required PDR is the maximum collision probability ( $P_C^{max}$ ) shifted over the distance of  $d_{TTS}$ , where  $d_{TTS}$  is the distance that corresponds to  $TTS$  (Time To Stop, see Fig. 3.6). The rationale behind our proposition is as follows.

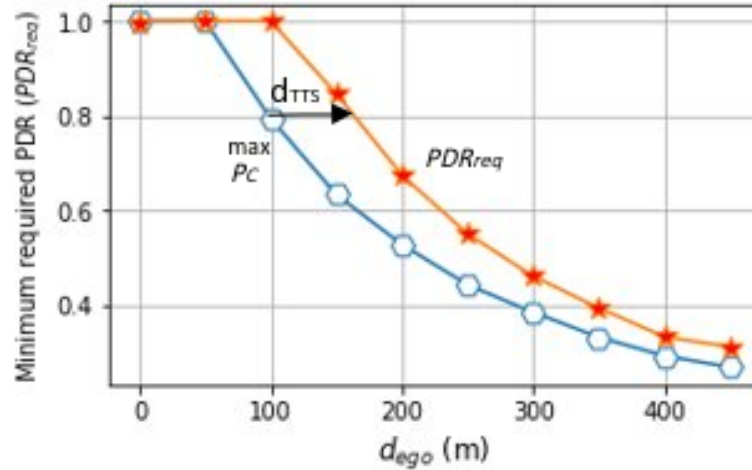


Figure 3.9: Safety application requirements using PDR,  $V_{ego} = 130$  Km/h

- It is pretty clear that the higher the collision risk is the higher the PDR requirement. We claim that the relationship between  $PDR_{req}$  and  $P_C^{max}$  is straight through: if the collision risk is 100%, the presence of the target vehicle has to be informed with the probability of 100% (i.e.,  $PDR_{req}$ ).
- After being alerted, the vehicle has to have at least the time to stop (TTS) that is needed to stop the vehicle before reaching the intersection point (see Fig. 3.6). This is why the minimum required PDR shall be a shifted function of the maximum collision probability.

Fig. 3.9 shows the minimum required PDR for a vehicle driving at the velocity of  $V_{ego} = 130$  Km/h derived from the maximum collision probability.

### Application requirement in terms of PIR

Now, similar to the case of PDR, we define the maximum allowed PIR as a function of collision probability (see Fig 3.10):

$$PIR_{req} = Inter_{max} - (Inter_{max} - Inter_{min}) \times P_C. \quad (3.5)$$

Here,  $Inter_{max}$  and  $Inter_{min}$  are the maximum and minimum message generation intervals. The values of  $Inter_{max}$  and  $Inter_{min}$  have been already provided by ETSI for CAMs and CPMs [100]: 1 s and 0.1 s, respectively. As can be seen in (3.5), PIR takes on smaller value for higher collision probability,  $P_C$ . In the extreme case, if  $P_C$  takes on 1, the maximum allowed PIR is the shortest message generation interval: 0.1 s. On the other hand, if  $P_C$  is 0, the maximum allowed PIR is the longest message generation interval, 1 s.

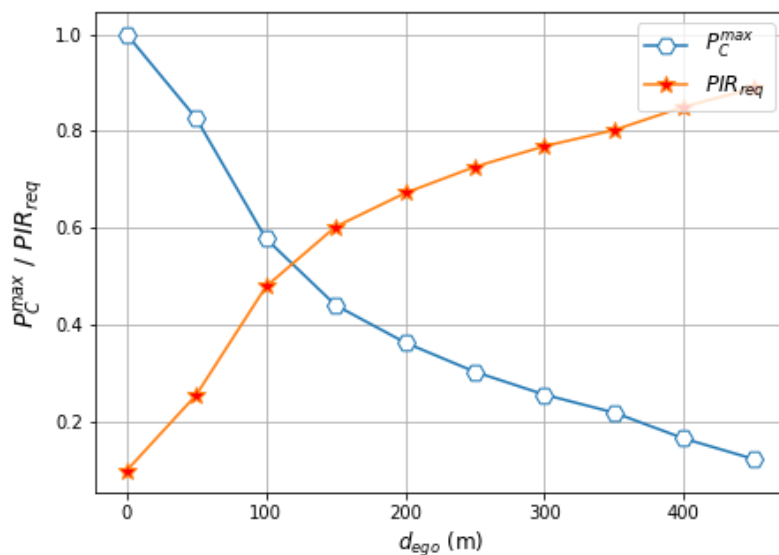


Figure 3.10: Safety application requirement in terms of PIR,  $V_{ego} = 110$  Km/h

Fig. 3.10 shows the maximum allowed PIR for a vehicle driving at the velocity of  $V_{ego} = 110$  Km/h derived from the maximum collision probability.

As a summary, in this section, we have established context in terms of requirements of collision avoidance applications. We proposed a model that calculates the maximum collision probability based on only the road layout and the ego-vehicle information. We then proposed to derive the application requirement expressed by the minimum required PDR and maximum allowed PIR from the maximum collision probability. In the next section, we are interested in environmental condition particularly to show the benefits of RSU contributions for CPS.

## **3.5 Collective perception service for connected vehicles and road side infrastructure**

### **3.5.1 Motivation**

Besides to the valuable advances in vehicles' design, road infrastructure is also under constant evolution. In adding to physical road signs (lane marks, speed limit signs, etc.), road signs are "digitally" available and be provided to vehicles using telecommunication technologies. Road infrastructure is going to be more and more intelligent, assisting and guiding vehicles in complex traffic situations for e.g., intersection crossing [101], railway crossing, longitudinal and collision avoidance etc.

According to the current ETSI draft specifications, CPM-generating ITS-Ss have to follow the same message generation rules regardless of their station types (V-ITS-S or R-ITS-S) [5]. We believe that this is probably not the best solution because V-ITS-S and R-ITS-S have very different characteristics. Indeed, sensor-equipped R-ITS-Ss have greater advantages than V-ITS-Ss because they can be installed in such a way that their sensor Field Of View (FOV) can strategically and efficiently cover road sections that are vulnerable to accidents. Moreover, roadside units have larger communication range and higher computing capability than vehicles [71] and furthermore, they can exploit the

emerging technological advancements particularly Multi-Access Edge Computing and the 5G technology [102, 103].

This section focuses on modeling environmental context, i.e. infrastructure availability, that allows RSU to contribute on CPS besides to vehicles. To do so, we develop an analytical model of the successful transmission probability of CPM over the IEEE 802.11p technology for both vehicle to vehicle (V2V) and infrastructure to vehicle (I2V) communications. The probability of successful transmission is greatly impacted by the network density and the frame size. Hence, we first formulate the CPM length for V2V and I2V communications, and then formulate the CPM success probability. we compare CPMs generated by vehicles and by RSUs, particularly their impacts on extending vehicles' perception.

### 3.5.2 Analytical model of V2V/I2V communication for collective perception service

#### Number of objects per message

For a sake of simplicity and without much loss of generality, the length of a CPM frame can be expressed as

$$L[\text{Bytes}] = A[\text{Bytes}] + B[\text{Bytes}] \times n_{pc} \quad . \quad (3.6)$$

Here,  $B$  is the length of one perceived object container and  $n_{pc}$  is the number of perceived object containers.  $A$  is the length of the remaining parts of the frame, which includes the management container, the sensor information container (if exists), the free space addendum container (if exists), the ITS PDU and other headers: Basic Transport Protocol (BTP) header, Geonetworking header, Medium Access Control (MAC) header, and Physical Layer Convergence Protocol (PLCP) header. The number of perceived object containers,  $n_{pc}$ , is equal to or smaller than the actual number of objects perceived by the ITS-S ( $n$ ). Indeed,  $n_{pc}$  needs to be adjusted such that the CPM length,  $L$ , does not



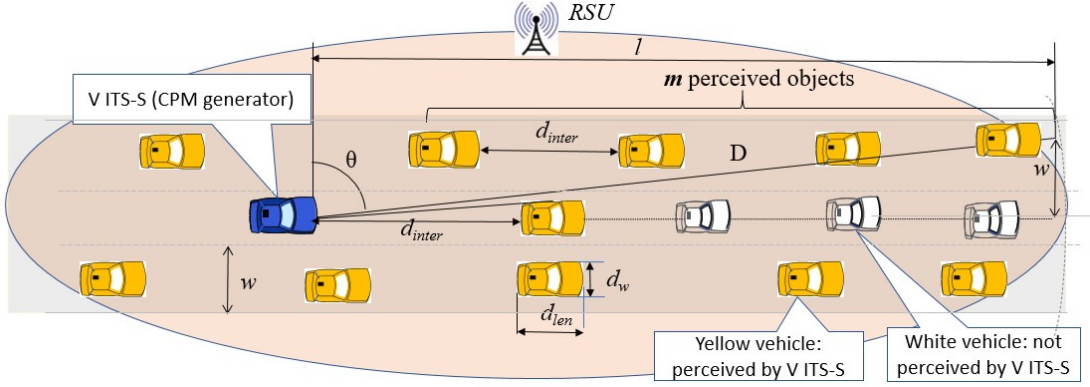


Figure 3.11: Calculating the number of perceived objects for a V-ITS-S.

exceed the maximum allowed frame size  $L_{max}$  determined by the technology in use.

We will now formulate the number of perceived objects ( $n$ ) for a V-ITS-S message generator and a R-ITS-S message generator. Let us imagine the scenario illustrated in Fig. 3.11, where vehicles are driving on a three-lanes straight road at inter-car distance  $d_{inter}$ . We assume that the vehicles have sensors with  $360^\circ$  of FOV [104, 105] and can detect objects in the range up to  $D_{max}^v$  as illustrated by grey zone in Fig. 3.11. Firstly, we shall consider that due to the sensor obstruction, a vehicle ITS-S can detect at most one vehicle on its front and on its back in its current lane. Secondly, the vehicle may detect multiple vehicles on its adjacent lanes. The number of vehicles detected on each lane depends on perception coverage,  $D_{max}^v$ , and vehicle density,  $\rho$ . Here, vehicle density is expressed by the relation  $\rho = \frac{1}{d_{inter} + d_{len}}$ , where  $d_{len}$  is the vehicle's length. As illustrated in Fig. 3.11, let  $m$  be the number of vehicles that the vehicle ITS-S perceives in its front left (interchangeably, front right, back left, or back right) on the parallel lane. Without loss of generality,  $m$  is initially estimated  $m$  for one side as follows

$$m = \rho \times l \quad (3.7)$$

where  $l$  is the length covered by the vehicle perception on the target side. Since detected vehicles have to be in the perception coverage and should not be obstructed by the vehicle

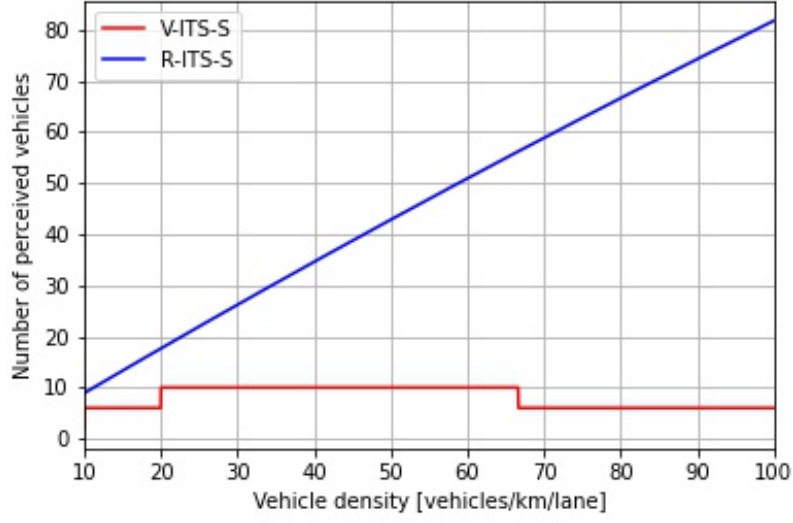


Figure 3.12: Number of perceived vehicles by a V-ITS-S and a R-ITS-S.

in front, the following constraints can be put.

$$\begin{cases} D = \sqrt{l^2 + w^2} \leq D_{max}^v \\ \tan(\theta) \leq \frac{2d_{inter}}{d_w} \end{cases} \quad (3.8)$$

Here,  $w$  is the lane width,  $d_w$  the vehicles width, and  $\tan(\theta) = \frac{l}{w}$ . The maximum length covered by the vehicle perception system that satisfies the above constraints is then given by

$$l = \min\left(\sqrt{D_{max}^v{}^2 - w^2}, \frac{2d_{inter}}{d_w}\right) \quad (3.9)$$

Finally, the expected number of detected vehicles for the target scenario is

$$n = \lfloor 4 \times m + 2 \rfloor, \text{ where } d_{inter} \leq D_{max}. \quad (3.10)$$

Assuming that roadside sensors can be installed close enough and high enough on the side of road such that there is no obstruction in its sensor FOV, we find

$$n = \left\lfloor 3 \frac{2D_{max}^{RSU}}{d_{len} + d_{inter}} \right\rfloor, \quad (3.11)$$

for the 3-lanes straight road.

Fig. 3.12 compares the number of objects perceived by a vehicle and by an RSU for

varying vehicle density. Table 3.2 lists the parameters used in the calculation. The figure clearly shows that the number of objects that an RSU can perceive linearly increases with the increase of the vehicle density. In contrast, the number of perceived objects for vehicles does not exceed 10 vehicles, and its lower in sparse or dense scenarios. As we

Table 3.2: System parameters.

Parameter	Value
RSU sensor coverage ( $D_{max}^{RSU}$ )	150 <i>m</i>
Vehicle sensor coverage ( $D_{max}^v$ )	100 <i>m</i>
RSU sensor FOV	360°
Lane width ( $w$ )	3 <i>m</i>
Vehicle length ( $d_{len}$ )	5 <i>m</i>
Vehicle width ( $d_w$ )	2 <i>m</i>
$A$ and $B$ in Bytes (see Eq.(3.6))	99 and 25
Maximum IEEE 802.11p frame size ( $L_{max}$ )	1500 <i>Bytes</i>
V-ITS-S sensing range ( $Rcs$ )	800 <i>m</i>
Contention window size ( $W$ )	15
Slot time ( $\sigma$ )	13 $\mu$ s
AIFSN	6
SIFS	32 $\mu$ s
Data rate	6 Mbps
RSU antenna height	3 m
Vehicle antenna height	1.5 m
Propagation model	Two-Ray

have found the number of perceived objects ( $n$ ), we are now ready to calculate the CPM length following Eq.(3.6). In Eq. (3.6),  $n_{pc}$  is equal to  $n$ , if the resulting  $L$  is smaller than the maximum allowed frame size,  $L_{max}$ . Otherwise,  $n_{pc}$  takes on the greatest integer value that satisfies  $L \leq L_{max}$ . Figure 3.13 compares the CPM lengths transmitted by a V-ITS-S and a R-ITS-S in varying vehicle density. As listed in Table 3.2,  $A$ ,  $B$ , and  $L_{max}$  take values on 99, 25, and 1500 bytes, respectively. Note that the values of  $A$  and  $B$  are taken from a real-world implementation of CPS [71]. 1500 bytes is the typical maximum frame size in Wi-Fi technologies.

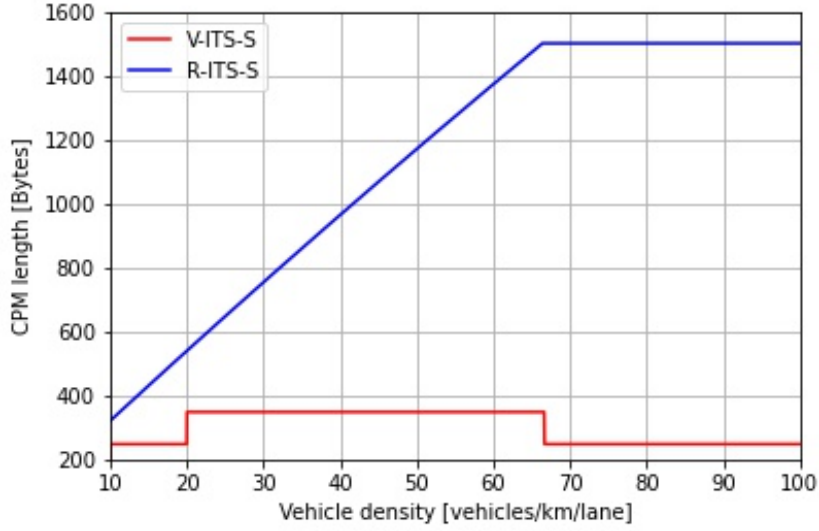


Figure 3.13: The CPM length transmitted by a vehicle ITS-S and a RSU ITS-S.

### Success probability

Now, we are interested in calculating the CPM success probability (or packet delivery ratio),  $P_s$ , which is the probability of successful reception of a transmitted CPM at individual receivers located within the communication range of the transmitter. Ignoring the hidden terminal problem and the capture effects, the success probability in the IEEE 802.11p technology is expressed by non-collision probability, which refers the case when the channel is accessed by only the desired transmitter in the receiver's sensing range ( $Rcs$ ). Let  $\tau$  be the channel access probability and the receiver has  $N$  neighbours (including the desired transmitter) in its sensing range. The success probability  $P_s$  can be found as:

$$P_s = (1 - \tau)^{N-1} \quad . \quad (3.12)$$

By taking account of the IEEE 802.11p behaviours particularly, the backoff counter is decremented at the start of slot time as well as the immediate channel access and the post-backoff procedures,  $\tau$  in the IEEE 802.11p can be calculated as follows [106]:

$$\tau = b_{-1} = \left[ \frac{1}{q} + 1 + \frac{(W-1)(2-p_i)}{2p_i} \right]^{-1} \quad . \quad (3.13)$$

Here  $W$  is the contention window size,  $p_i$  is the channel idle probability, and  $q$  is the probability of having a pending packet in the transmission queue. Assuming that packets are generated following the Poisson process, we get

$$q = 1 - e^{-\lambda Y_s}. \quad (3.14)$$

Here  $\lambda$  is the packet generation rate and  $Y_s$  is the average channel service time, which can be found

$$Y_s = (1 - p_i)(T + AIFS) + p_i\sigma \quad , \quad (3.15)$$

where  $T$  is the time required for a transmission of a CPM frame and  $\sigma$  is the slot time [107].  $T$  depends on the frame size ( $L$ ) and the data rate (the default data rate of the 802.11p technology is 6 Mbps). AIFS (arbitration inter-frame space) is the shortest time interval between frames and it is found as

$$AIFS = AIFSN \times \sigma + SIFS \quad , \quad (3.16)$$

where AIFSN is arbitration inter-frame spacing number and SIFS is short inter-frame space, which are fixed values defined in the standard IEEE 802.11p (see Table 3.2). Finally, the channel is idle if none of the nodes in the carrier sensing range of the transmitter accesses to the channel:

$$p_i = (1 - \tau)^N. \quad (3.17)$$

Eqs. (3.12) - (3.17) allow us to calculate the CPM success probability for varying densities, i.e., for varying  $N$  and  $T$ .

Fig. 3.14 shows the mean CPM success probability when CPMs are transmitted by vehicles as well as the RSU (denoted as V2X) and by only the RSU (denoted as I2V-only). Supposing that the channel is used only for CPM transmissions, we can obtain 100% of success probability in the I2V-only case, because there is no contention and hence no collision. On the other hand, in V2X, as vehicles also transmit CPMs, the success probability degrades with the increase of the vehicle density (see Eq. 3.12). It is

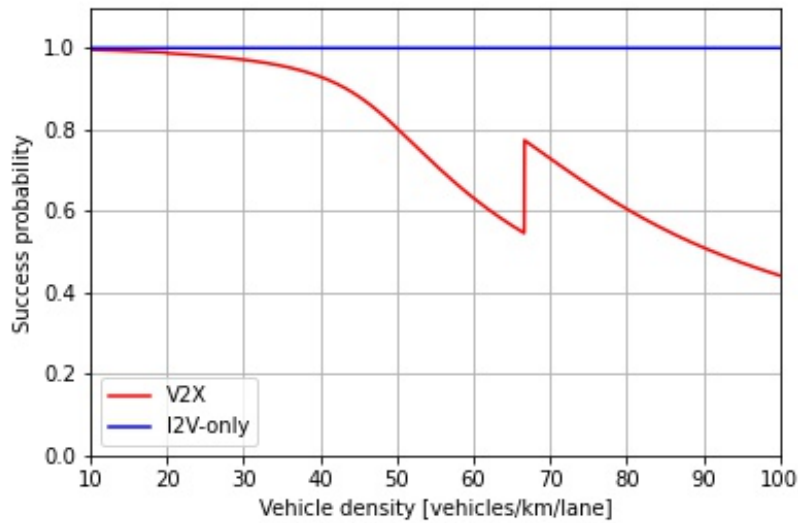


Figure 3.14: CPM success probability for V2X and I2V-only communications.

interesting to note that the degradation of success probability is no smooth, particularly there is "a jump" at 67 [veh/km/lane], where the number of perceived vehicles drops from 10 to 6 for V-ITS-S (see Fig. 3.12).

### 3.6 Conclusion

In this chapter, we identified context aware system architecture. We presented context cycle consisting on 3 phases context acquisition, context reasoning and system control and integrated context awareness on the management layer of the proposed architecture. Also, after identifying main contexts for controlling communication targeting collision avoidance applications, we have analysed their potential impacts: 1) Application requirements can be modeled based on minimum required PDR and PIR as function of maximum allowed speed, vehicle density and road layout. 2) I2V communication can outperform V2V communication in terms of number of objects per CPM and PDR when RSU is available on the environment. In the next chapter, we will present the design and implementation of algorithms that take into account the previously identified context(s)

in order to control communication parameters, particularly CPM generation rate and content selection (chapter 4). Finally, a simulation study will be provided to evaluate the proposed schemes in chapter 5.

## Chapter 4

# Contextual communication for CPM dissemination control

### Contents

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## 4.1 Introduction

In this chapter, we are interested in designing and developing CPM content selection algorithms that build cooperative perception while avoiding channel congestion taking into account modeled contexts. First, we present CPM content selection architecture describing the modules that contribute to the selection process of CPM data. Then, context aware schemes which differ in terms of context utilisation and content selection algorithm are proposed. We start with describing algorithms that adjust CPM generation rate based on channel status *CBR-binary* and CPM content *CBR-selective*. Then, we focus on infrastructure availability context and present *Infra-selective* scheme. Finally, we propose a multi-context based algorithm that takes into account not only radio resource but also infrastructure availability denoted as *CBR & Infra selective*.

## 4.2 CPM content selection architecture

The target CPM content selection system architecture for a vehicle is depicted in Fig. 4.1. This architecture details schema selection process within communication profile adaptation module described in Fig 3.4 of chapter 3. It should be noted that the architecture may be applied to roadside infrastructure and vehicles providing CP service. Nevertheless, roadside infrastructure has higher communication, perception, and computing capability and lower density compared to vehicles, we consider that a CPM content selection control should be applied particularly to vehicles that tend to overload wireless channel whereas their contribution for cooperative perception is lower than that of roadside infrastructure.

As can be seen in the figure, a vehicle has local perception module that processes data from the on-board sensors and creates lists of objects perceived by the sensors. The vehicle also has *collective perception service (CPS)* consisting of a client module (*CPS*

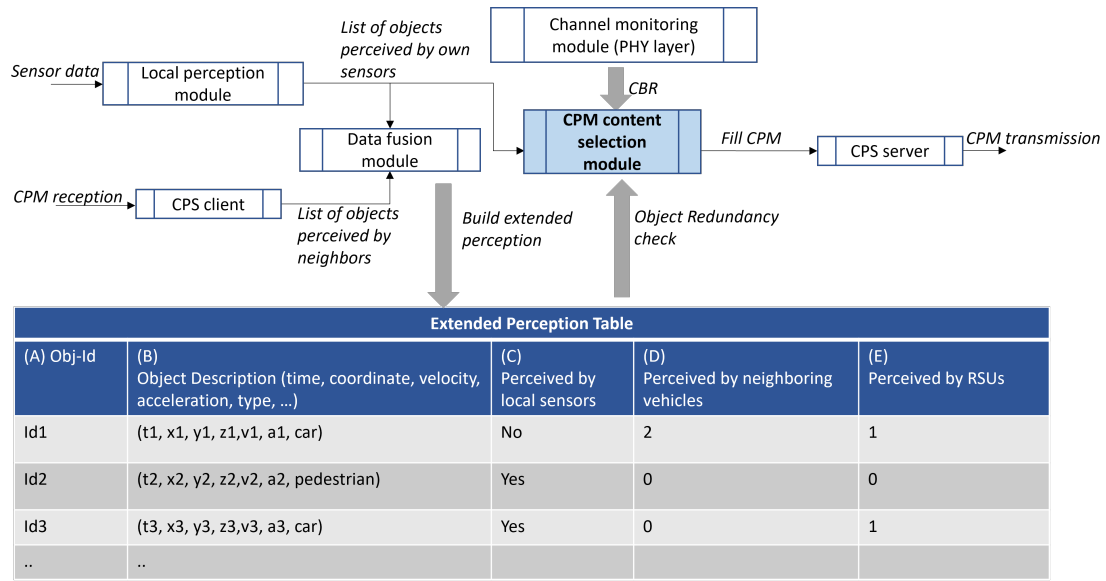


Figure 4.1: System diagram for Context-aware CPM generation and content selection

*client*), which processes received CPMs, and a server module (*CPS server*), which is responsible for generating and transmitting CPMs. *Data fusion module* fuses the data obtained from the local perception module and the CPS client, and maintains *extended perception table*. Particularly, the table consists of five columns: (A) - (E) (see Figure 4.1) that are:

- (A) Object ID: an identification provided by the data fusion module,
- (B) Object description: describes the object, particularly perceived time, position, velocity, type, dimension, etc.,
- (C) Perceived by local sensors: indicates if the object is detected by the ego vehicle,
- (D) Perceived by neighboring vehicles: the number of neighboring vehicles that detected the object,
- (E) Perceived by RSUs: the number of roadside infrastructure that detected the object.

Finally, upon reception of a list of objects detected by the *local perception module*, CPM

content selection module fills outgoing CPMs and provides the *CPS server* for a transmission.

While it may include all the objects perceived by the local sensors (*Default* scheme), in the next sections, we propose different context aware schemes, *Infra-selective*, *CBR-Binary*, *CBR-selective*, *CBR & Infra selective*, that consider one or more contexts as described below.

- *Infra-selective* takes into account only infrastructure availability,
- *CBR-Binary* and *CBR-selective* take into account only radio resource availability, and
- *CBR & Infra selective* takes into account both infrastructure availability and radio resource availability .

### 4.3 Context aware CPM content selection scheme using infrastructure availability

*Infra-selective* takes into account the presence of roadside infrastructure that is providing CP service. Since infrastructure can be installed in such a way so that it has an extended (and often line of sight (LoS)) communication and sensor coverage [108], if the same object has been already announced by the infrastructure, there is not much value to add it by the ego vehicle with a transmission of a CPM containing that object. Indeed, in the previous section, we showed that when CPMs are generated and transmitted by roadside infrastructure, vehicles in its communication coverage do not really need to send CPMs because the infrastructure alone can provide extended perception without needing much of radio resource. Therefore, as shown in Algorithm 1, the scheme assesses if the object (detected by the ego vehicle) has been also detected by a roadside infrastructure. Specifically, as can be described in Algorithm 1, for each object, the *CPM content se-*

lection module verifies if an infrastructure has detected the same object by referring to the column (E) of the *extended perception table*. If an object,  $a_i$ , in the list  $A$ , has been detected by an infrastructure, the  $a_i$  is removed from the list. Once the above verification procedure has been finalised and the list  $A$  is not empty, the objects contained in the list will be included in a CPM and be transmitted.

---

**Algorithm 1:** *Infra-selective* algorithm

---

```

1 /* The objects that have not been perceived only by roadside
   infrastructure will be included in the CPM. If there is no such
   an object, no CPM will be transmitted. */
Input :  $A=[a_i], i = 1, 2, \dots, n$ , a list of objects (more precisely, object IDs),
         perceived by the local perception module.
Output:  $A$ , list of objects to include in an outgoing CPM; if objectList is
         empty, CPM will not be transmitted.
2  $objectList = \text{InfraSelective}(A)$ 
3 if  $size(objectList) > 0$  then
4   | Fill a CPM with the objects in objectList and provide the CPS server module
   | for a transmission.
5 end if
6 Function  $\text{InfraSelective}(A)$ :
7   | for  $i \leftarrow 0$  to  $n - 1$  do
8     |   if  $Column\_E(a_i) > 0$  then
9       |   |  $A.remove(a_i)$  // the object is detected by an infrastructure;
       |   | remove the object from the list.
10    |   end if
11    | end for
12    | return  $A$ 
13 End Function

```

---

#### 4.4 CBR-binary scheme

As depicted in Fig. 4.2, the *CBR-binary* algorithm will basically decide whether or not to send CPMs. The decision is made based on a control function of minimum new detected objects (minimum threshold)  $O_{min}$ . If the number of objects detected only by ego vehicle, i.e., none of the neighboring vehicles/RSU detected the same object, (N) exceeds  $O_{min}$ ,

then the CPM should be sent. Otherwise the algorithm will not send the CPM.  $O_{min}$  is determined based on current CBR value. For example, in the case of CBR value is high (e.g.  $CBR > 0.7$ ),  $O_{min}$  increase and in the case of CBR value is low (e.g.  $CBR < 0.6$ )  $O_{min}$  decrease.

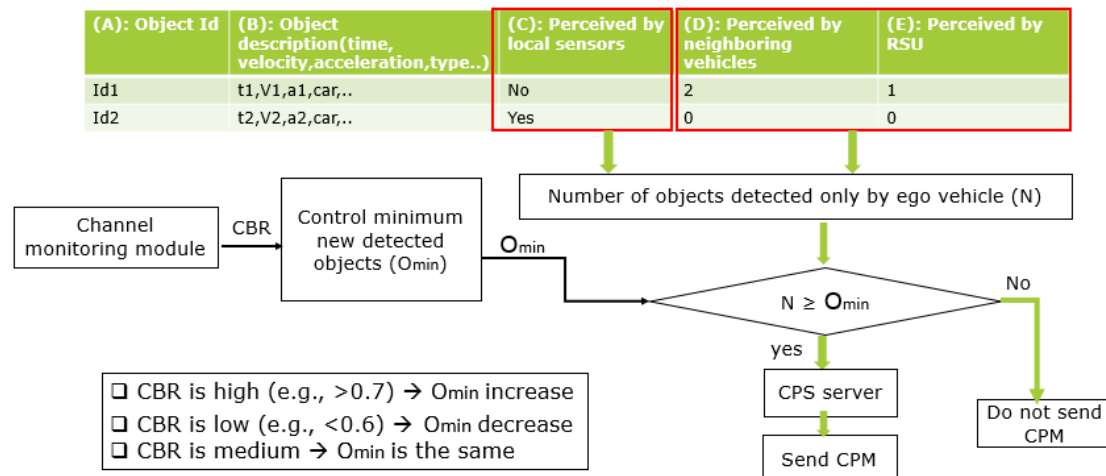


Figure 4.2: *CBR-binary* algorithm flowchart

Specifically, upon reception of a list of objects,  $A=[a_i]$  perceived by own sensors (from the *local perception module*), the CPM content selection module determines if it shall send a CPM containing those objects (by the *CPS server*, see Figure 4.1).

As can be described in Algorithm 2, for each object, the *CPM content selection module* verifies, by referring to the columns (D) and (E) of the *extended perception table*, if any of its neighbors (vehicle or roadside infrastructure) has detected the same object. Once the above verification procedure has been finalised, the CPM content selection module compares the number of objects that are detected only by ego vehicle against a threshold value *ThresholdBinary*. If the number of such objects does not exceed *ThresholdBinary*, no CPM will be transmitted. Otherwise, the CPM content selection module fills a CPM with the objects in the  $A$  list and provides it to the *CPS server* for a transmission.

*ThresholdBinary* is adjusted by the *CPM content selection module* each time when a

---

**Algorithm 2:** *CBR-binary* scheme

---

```
1 /* A CPM is transmitted if only if the number of objects that are
   uniquely detected by the ego-vehicle (i.e., none of the
   neighboring vehicles/RSU detected the same object) exceeds a
   threshold value, ThresholdBinary. */
   Initialise: ThresholdControl(Init, InitThrbinary,  $\delta_{binary}$ )
   Input    :  $A = [a_i], i = 1, 2, \dots, n$ , // a list of objects (more precisely,
             object IDs), perceived by the local perception module
2 shallSend=CbrBinary(A)
3 if ShallSend == True then
4   | Fill a CPM with the objects in A and provide the CPS server module for a
   | transmission.
5 end if
6 Function CbrBinary(A):
7   | ThresholdBinary=ThresholdControl(GetThr,0,0)
8   | count = 0
9   | shallSend = True
10  | for  $i \leftarrow 0$  to  $n - 1$  do
11    | if ColumnD( $a_i$ ) > 0 or ColumnE( $a_i$ ) > 0 then
12      | | count++ // the object is perceived by a neighbor.
13    | end if
14  | end for
15  | if  $size(A) - count \leq ThresholdBinary$  then
16    | | shallSend = False
17  | end if
18  | return shallSend
19 End Function
```

---

new CBR value is notified by the *PHY layer channel monitoring module*. The threshold control algorithm is depicted in Algorithm 3. In fact, the same algorithm is used for all the schemes that consider CBR i.e., *CBR-binary*, *CBR-selective*, and *CBR&Infra Selective*. As can be seen in the Algorithm 3, the threshold control algorithm has two parameters *Threshold* and a step parameter  $\delta$ . The *Threshold* parameter is incremented or decremented by *delta* each time a new CBR value is available. Therefore, depending on the  $\delta$  value, *Threshold* can be modified quickly or slowly. It is up to each scheme to define the initial value of *Threshold* and the value of  $\delta$ . Indeed, as described in Algorithm 2, *CBR-binary* sets the initial value of *Threshold* and the step parameter  $\delta$  to *InitialThreshold<sub>binary</sub>* and *delta<sub>binary</sub>*, respectively.

As can be seen in the Algorithm 3, the threshold control algorithm increments *Threshold* by  $\delta$ , if the current CBR exceeds a predefined maximum CBR threshold, *CBR<sub>max</sub>* (channel is congested).

On the other hand, *Threshold* is decremented by  $\delta$ , if the CBR value is below a predefined minimum CBR threshold, *CBR<sub>min</sub>* (i.e., the channel is sparse). If the CBR is in the range of  $[CBR_{min}, CBR_{max}]$ , *Threshold* is kept unchanged. Therefore, as it is described in Algorithm 2, if the channel is sparse, the *ThresholdBinary* takes on a lower value and hence the *CBR-binary* scheme tends to transmit CPMs even if it contains few (uniquely detected) objects. On the contrary, if the channel is congested (i.e., CBR exceeds *CBR<sub>max</sub>*) the *ThresholdBinary* value takes on a higher value, requiring high number of objects be uniquely detected by the ego-vehicle in order to transmit the CPM. Finally, it should be noted that the scheme decides whether or not to transmit the complete list of detected objects. Therefore, the scheme controls the transmission opportunity (the transmission interval) of CPMs but not CPM contents.

---

**Algorithm 3:** *Threshold Control* function

---

**Input** :  $CBR$   
**Output:**  $Threshold$

```
1 /* Each time, when a new  $CBR$  value is available, the  $Threshold$ 
   value is adapted. */
2 if a new  $CBR$  value is available then
3   if  $CBR < CBR_{min}$  then
4      $Threshold = \max(0, Threshold - \delta)$  // the channel is sparse, reduce
     the threshold.
5   else if  $CBR > CBR_{max}$  then
6      $Threshold += \delta$  // the channel is congested, increase the
     threshold.
7 end if
8 /* Interacts with external functions ( $CBR - Binary$  or
    $CBR - Selective$ ) either to initialise  $Threshold$ , and the step
   parameter,  $\delta$  or to provide the current  $Threshold$  value. */
9 Function  $ThresholdControl(Key, Thr, ValDelta)$ :
10 | if  $Key = "Init"$  then
11 |    $Threshold = Thr$ 
12 |    $\delta = ValDelta$ 
13 | else if  $Key = "GetThr"$  then
14 |   return  $Threshold$ 
15 End Function
```

---



## 4.5 CBR-selective scheme

As depicted in Fig. 4.3, similarly to *CBR-binary*, *CBR-selective* will take into account of channel condition. However, *CBR-selective* algorithm will select the object to be included in the CPM. The decision is made based on a control function of the occurrences of that object (maximum threshold)  $Occ_{max}$ , meaning the number of neighboring vehicles and RSUs detecting the same object is below a certain threshold. The threshold value is defined from the channel busy ratio. For instance, in the case of a high value of CBR (e.g.  $CBR > 0.7$ ),  $Occ_{max}$  decrease and in the case of low value of CBR (e.g.  $CBR < 0.6$ )  $Occ_{max}$  increase. It may decide to not transmit a CPM, if all the detected objects have been announced by a sufficient number of neighboring vehicles/infrastructure.

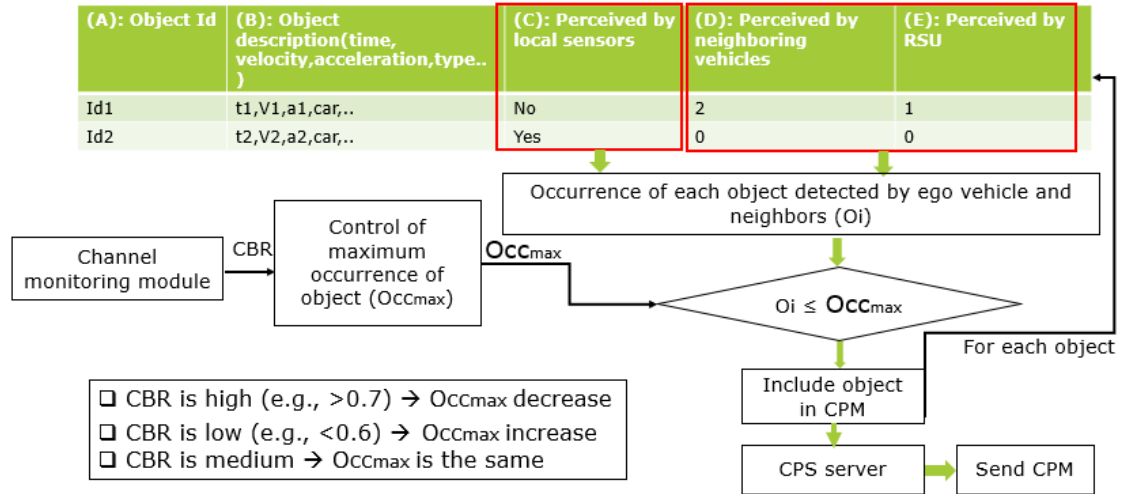


Figure 4.3: *CBR-selective* algorithm flowchart

Similar to the *CBR-binary* scheme, upon reception of a list of objects detected by the ego vehicle,  $A=[a_i]$  (from the *local perception module*), the *CPM content selection module* determines which objects to include in a CPM (see Figure 4.1).

As can be described in Algorithm 4, for each object, the module verifies, by referring to the columns (D) and (E) of the extended perception table if its neighbors (vehicle or RSU) have detected the same object. If the object,  $a_i$ , has been detected by more

---

**Algorithm 4:** *CBR-selective* algorithm

---

```
1 /* The objects that have been perceived only by the local sensors or
   the number of neighbors that detected the same object is below a
   threshold value, Threshold, will be included in the CPM. If there
   is no such an object, no CPM will be transmitted. */
Initialisation: ThresholdControl(Init, InitThrselective,  $\delta_{selective}$ )
Input           :  $A = [a_i]$ ,  $i = 1, 2, \dots, n$ , a list of objects (more precisely, object
                   IDs), perceived by the local perception module.
Output         :  $A$ , the list of objects to include in an outgoing CPM; if the list is
                   empty, CPM will not be transmitted.
2 objectList = CbrSelective( $A$ )
3 if size(objectList) > 0 then
4   | Fill a CPM with the objects in objectList and provide the CPS server module
   | for a transmission.
5 end if
6 Function CbrSelective( $A$ ):
7   | ThresholdSelective = ThresholdControl(GetThr, 0, 0)
8   | for  $i \leftarrow 0$  to  $n - 1$  do
9     |   numRedundance = ColumnD( $a_i$ ) + ColumnE( $a_i$ )
10    |   if numRedundance > ThresholdSelective then
11      |      $A.remove(a_i)$  // the object has been perceived by a higher
      |     than Threshold number of neighbors; remove the object from
      |     the list.
12    |   end if
13  | end for
14  | return  $A$ 
15 End Function
```

---

than *ThresholdSelective* neighbors, the object is removed from the list  $A$ , and not considered for inclusion in an outgoing CPM. Once the above verification procedure has been finalised and if the list  $A$  is not empty, the objects contained in the list will be included in a CPM and be transmitted by the CPM server module. Otherwise, the *CPM content selection module* fills a CPM with the remaining objects in the list and provides to the *CBM-server* for a transmission.

Same as the *CBR-Binary* scheme, *ThresholdSelective* is adjusted by the *CPM content selection module* by the threshold control algorithm detailed in Algorithm 3. The initial value of *Threshold* and the step parameter  $\delta$  are set to predefined values  $InitialThreshold_{selective}$  and  $\delta_{selective}$ .

As mentioned, *ThresholdSelective* takes on a lower value when the channel is sparse, and a higher value when the channel is congested. Therefore, in the *CBR-selective* scheme, higher level of redundancy is allowed if the channel is sparse and the redundancy is highly restricted if the channel is congested.

## 4.6 *CBR&Infra selective* scheme for CPM content selection

It is possible to improve CPS performances (using context aware CPM content selection schemes) in terms of CBR, PDR and awareness rate by taking into account only one context, either radio resource availability context or infrastructure availability context. However, communication performances in terms of PDR may not be satisfying to reach requirements of road safety applications as discussed in chapter 3, especially in dense conditions. Indeed, for collision avoidance application, such requirement should be respected in all conditions to ensure sharing updated and recent safety information. To overcome such limitations, more than one context shall be considered in order to achieve maximum CPS performance and hence satisfy application requirements. Motivated by this, in this section, we design a multi-context scheme *CBR&Infra selective* for CPM

content selection. The latter takes into account both radio resource and environmental contexts.

*CBR&Infra-selective* is, as its name suggests, a hybrid algorithm of the *Infra-selective* and *CBR-selective* algorithms detailed in the previous sections. As shown in Fig. 4.4 the current algorithm will take into account RSU availability in adding to the other contexts. It will first compare the number of neighboring vehicles detecting the same object to a given threshold ( $Occ_{max}$ ), which is defined by CBR. It will further check if the object is detected by an RSU. If the object detection occurrence is below the threshold  $Occ_{max}$  and if the object is not detected by a RSU, the object is included in a CPM.

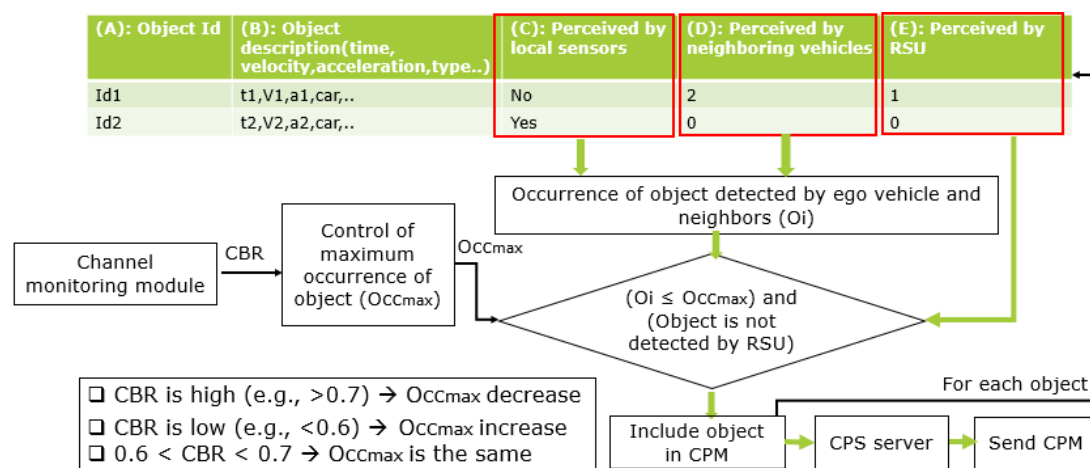


Figure 4.4: CBR&Infra selective algorithm flowchart

Similar to the previous algorithms, upon reception of a list of objects detected by the ego vehicle,  $A=[a_i]$  (from the *local perception module*), the CPM content selection module determines which objects to include in a CPM (see Figure 4.1). As shown in Algorithm 5, the *CPM content selection module* will first run the *CBR-selective* algorithm targeting only the column (D) of the *extended perception table*. In other words, the algorithm verifies detection redundancy level of the object detected by the ego-vehicle and the neighboring vehicles and removes the object if the level exceeds a threshold value *ThresholdSelective*. *ThresholdSelective* is permanently adapted based on the measured

CBR by the threshold control algorithm 3. The *CPM content selection module* will then further run *Infra-selective* algorithm and removes the objects from the list that have already been informed by the roadside infrastructure. Finally, if the resulting list is not empty, the module fills a CPM with the remaining objects in the list and provide the CPM to the *CPS server* for a transmission.

## 4.7 Conclusion

In this chapter, different context aware CPM content selection schemes are proposed where two types of context are considered: resource availability calculated using CBR and environmental context consisting on RSU availability and traffic density. Such schemes could be integrated in context aware system architecture depicted in chapter 3, particularly in management layer where intelligent decisions concerning the optimisation of communication parameters should be taken. In order to confirm the effectiveness of these algorithms for improving CPS performance and hence CPM dissemination, in the next chapter, we conduct simulation study that evaluates the proposed schemes and compare their performances against a non context-aware scheme (*Default*) performance.

---

**Algorithm 5:** *CBR&Infra selective* algorithm

---

```
1 /* Check if vehicle received a CPM from RSU. If not, record
   occurrence of each object received in CPM. Otherwise, record
   occurrence of each object received in CPM. If there is no such an
   object, no CPM will be transmitted. */
Initialisation: ThresholdControl(Init, InitThrselective,  $\delta_{selective}$ )
Input :  $A=[a_i]$ ,  $i = 1, 2, \dots, n$ , a list of objects (more precisely, object
         IDs), perceived by the local perception module.
Output : objectList, list of objects to include in an outgoing CPM; if
         objectList is empty, CPM will not be transmitted.
2 objectList=CbrInfraSelective(A)
3 if size(objectList) > 0 then
4   | Fill a CPM with the objects in objectList and provide the CPS server module
   | for a transmission.
5 end if
6 Function CbrInfraSelective(A):
7   | ThresholdSelective=ThresholdControl(GetThr,0,0)
8   for  $i \leftarrow 0$  to  $n - 1$  do
9     | numRedundance = Column_D( $a_i$ ) if
     | numRedundance > ThresholdSelective then
10    | | A.remove( $a_i$ ) // the object has been perceived by a higher
     | | than ThresholdSelective number of neighboring vehicles;
     | | remove the object from the list.
11    | end if
12  end for
13  objectList=InfraSelective(A)
14  return objectList
15 End Function
16 Function InfraSelective(A):
17  for  $i \leftarrow 0$  to  $n - 1$  do
18  | if Column_E( $a_i$ ) > 0 then
19  | | A.remove( $a_i$ ) // the object is detected by an infrastructure;
     | | remove the object from the list.
20  | end if
21  end for
22  return A
23 End Function
```

---

# Chapter 5

## Simulation evaluations and results

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## 5.1 Introduction

In this chapter, we focus on evaluating our proposed analytical models presented in chapter 3 and the context aware schemes proposed in chapter 4 using simulation approach. This step is very important to confirm the effectiveness of the schemes for the optimal control of CPM transmission as well as content selection based on context recognition. We conducted simulations using Veins simulator [109], which combines the SUMO traffic simulator [110] and the OMNeT++ network simulator [111]. The architecture of Veins is described in Fig. 5.1 [109]. As shown in the figure, SUMO and OMNeT++ run on parallel while exchanging information via the TraCi protocol.

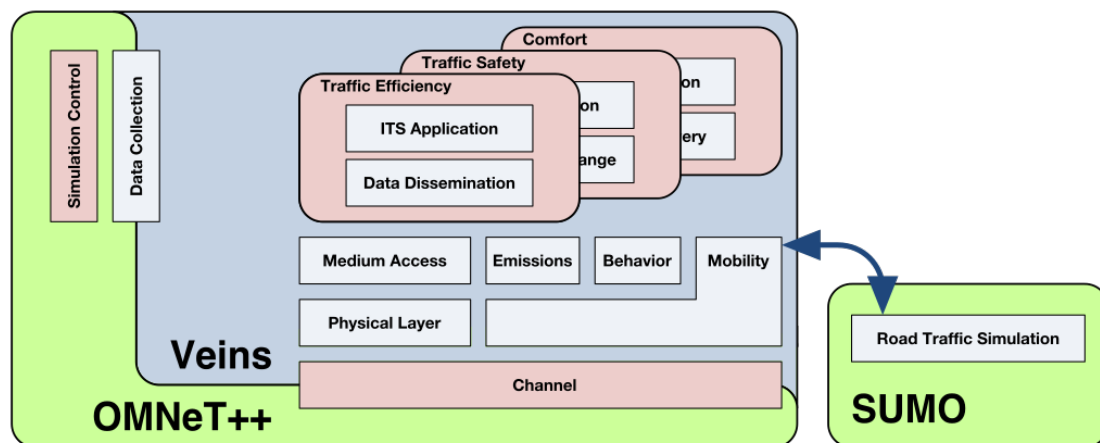


Figure 5.1: Veins architecture

## 5.2 Evaluation of DCC mechanisms w.r.t the application requirements

In chapter 3, we formulated models on requirements of collision avoidance applications in terms of PDR and PIR. In this section, we are interested in applying the models in order to see their impacts. Particularly, as for road safety, we are interested in verifying if the communication performances are meeting the application requirements provided



by the models.

### 5.2.1 System setting and performance metrics

We are interested in evaluating whether the performances of the existing CAS strategies meet the defined requirements. Particularly, we are interested in the following three CAS strategies:

- Periodic-CAM: The CAS generates CAM packets at every 100 ms.
- Reactive-DCC: The CAS monitors the channel load (CBR) and controls the CAM generation rate following a lookup table.
- Adaptive-DCC: The CAS monitors the channel load (CBR) and controls the CAM generation rate based on a linear adaptive algorithm [80].

In [80], ETSI reported the performances of the above mentioned three CAS strategies that were evaluated using computer simulations. The performances of Periodic-CAM and Reactive-DCC were evaluated targeting a 6-lanes highway scenario for different traffic densities: sparse (10 cars/lane/km), medium (20 cars/lane/km), dense (40 cars/lane/km) and extreme (67 cars/lane/km).

The ITS G5 (IEEE 802.11p) technology is used as the V2X communication technology. All the vehicles embed on-board sensors. Table 5.1 lists the simulation parameters, including Road length, number of lanes and propagation model.

Finally, the evaluation performance metrics are the following:

- Packet Delivery Ratio (PDR): indicates the reliability of V2X communications, measured for each pair of transmitter and receiver as the ratio between the number of received packets over the number of transmitted packets.
- Packet Inter Reception time (PIR): indicates the interval of time elapsed between two successful message reception.

Table 5.1: Simulation parameters.

Parameter	Value
Road length	1000 <i>m</i>
Number of lanes	4
Number of directions	2
Inter-car distance	10, 20, 45, 100 <i>m</i>
Lane width ( <i>w</i> )	3 <i>m</i>
Vehicle length ( <i>d<sub>len</sub></i> )	5 <i>m</i>
Vehicle width ( <i>d<sub>w</sub></i> )	2 <i>m</i>
Data rate	6 Mbps
Propagation model	Two-Ray
Transmission power	20 dBm

## 5.2.2 Results

### Evaluating CAS performances against PDR requirement

In Figs. 5.2 and 5.3, we compare the performances of Periodic-CAM (noted Periodic) and Reactive-DCC (noted Reactive) against the application requirement formulated in chapter 3 using PDR metric. In calculating the application requirement for the different traffic density scenarios, we applied GreenShield model [112] that converts the density (*D*) to a velocity (*v*):

$$v = V_{max} - \left( \frac{V_{max}}{D_j} \right) D \quad (5.1)$$

Here,  $V_{max}$  is the free flow speed (i.e., the maximum allowed speed) and  $D_j$  is the jam density. The former is fixed to 130 Km/h and the latter is calculated assuming that bumper-to-bumper distance is 2 meters, which leads to a density of 143 cars/lane/km.

The horizontal axis of the figures is the transmitter (Tx) and receiver (Rx) separation distance (*d*). As for application requirement, we are always interested in the worst case scenario, which is found for 90-degree crossing:

$$d = \sqrt{d_{ego}^2 + d_{tar}^2} \quad (5.2)$$

Fig. 5.2 shows that periodic-CAM satisfy application requirement only in sparse scenario

and never meets the requirement in extreme and dense scenarios. As for medium scenario, the Periodic-CAM does not meet the requirements for shorter Tx and Rx separation distances.

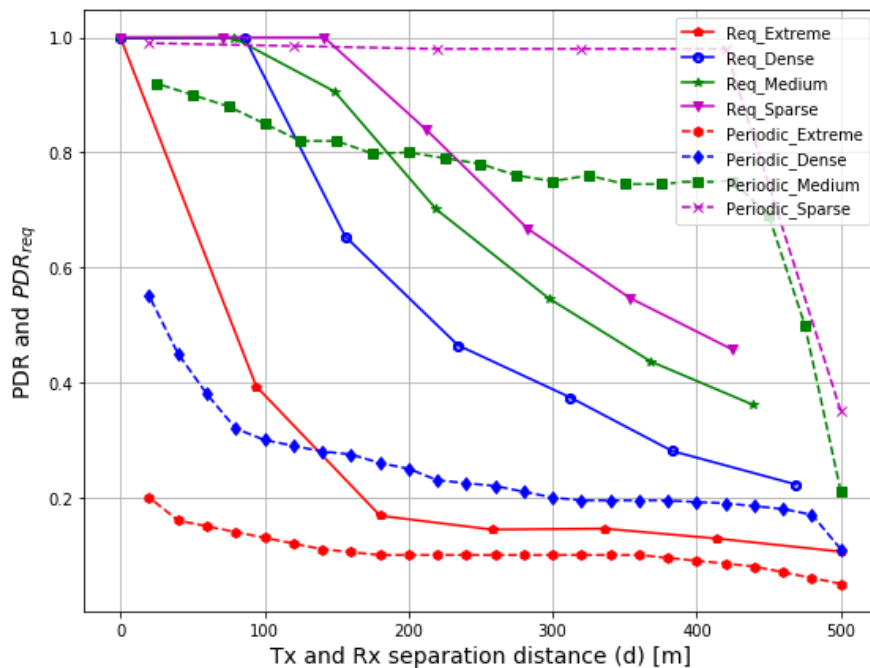


Figure 5.2: Comparing PDR of Periodic-CAM against the application requirement ( $PDR_{req}$ ).

Fig. 5.3 shows, on the other hand, we can say that reactive-DCC algorithm meets the application requirement in the extreme density scenario. But it suffers in the remaining scenarios especially for shorter Tx and Rx separation distances (shorter than 120-150 meters).

In [80], the authors evaluated the packet error rate ( $PER = 1 - PDR$ ) of Adaptive-DCC targeting a scenario, where vehicles run at the average speed of 65km/h on a S-shaped road. Fig. 5.4 compares the Adaptive-DCC performances against the corresponding application requirement. In contrast to periodic-CAM and Reactive-DCC, Adaptive-DCC meets the application requirement for the evaluated scenario. This result however cannot guarantee that the algorithm would meet the application requirement for any

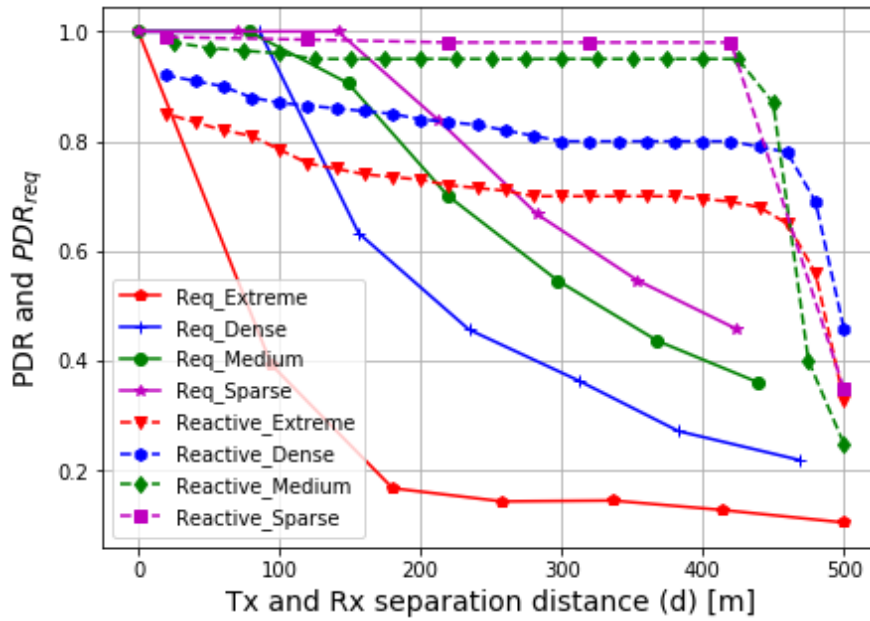


Figure 5.3: Comparing PDR of Reactive-DCC against the application requirement ( $PDR_{req}$ )

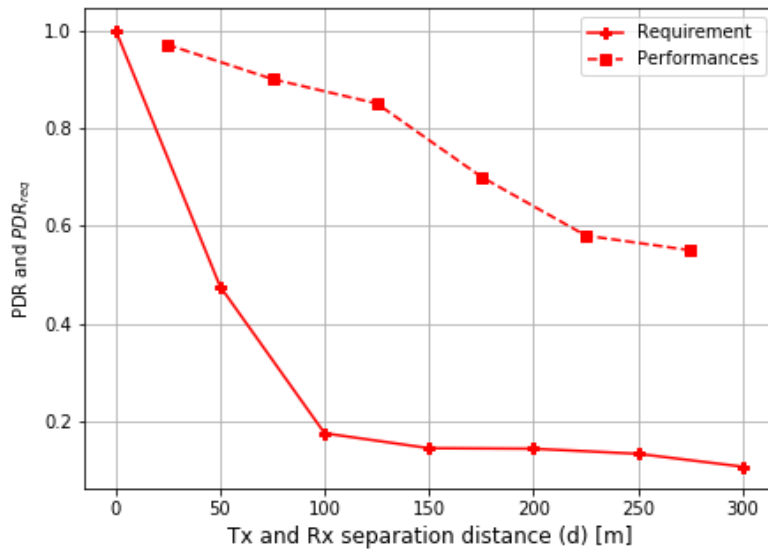


Figure 5.4: Comparing PDR of Adaptive-DCC against the application requirement ( $PDR_{req}$ )

traffic scenario. It may look like presenting a need of searching different traffic scenarios with an attempt of determining the cases where the algorithm (e.g., Adaptive-DCC) fails to meet the application requirement.

### Evaluating CAS performances against PIR requirement

In this section, we extend our evaluation study and compare CAS performances against application requirement in terms of maximum allowed PIR for Periodic-CAM and Reactive-DCC strategies.

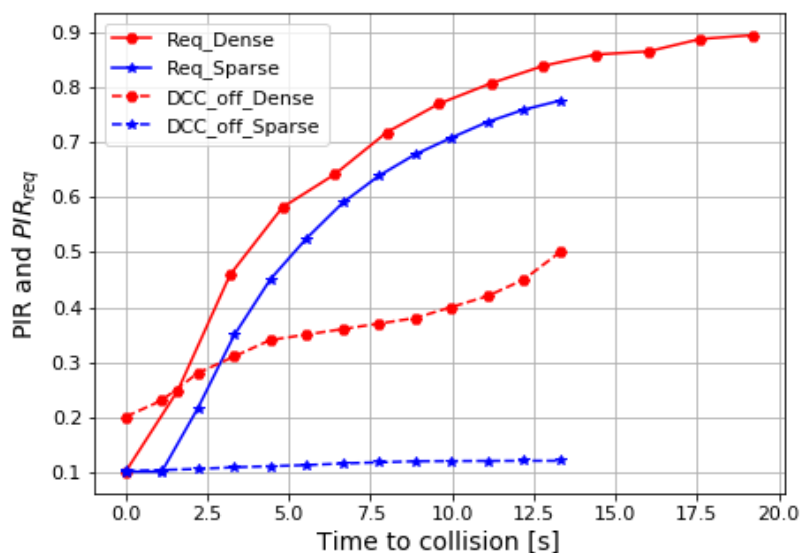


Figure 5.5: Comparing performances of Periodic CAM against the application requirement ( $PIR_{req}$ )

In Fig. 5.5 and Fig. 5.6, we compare the performances of Periodic-CAM and DCC-reactive against the application requirement formulated in the previous section using PIR metric.

Fig. 5.5 shows that the periodic-CAM meets the application requirement when time to collision TTC is greater than 2s in both sparse and dense density scenarios. However, for

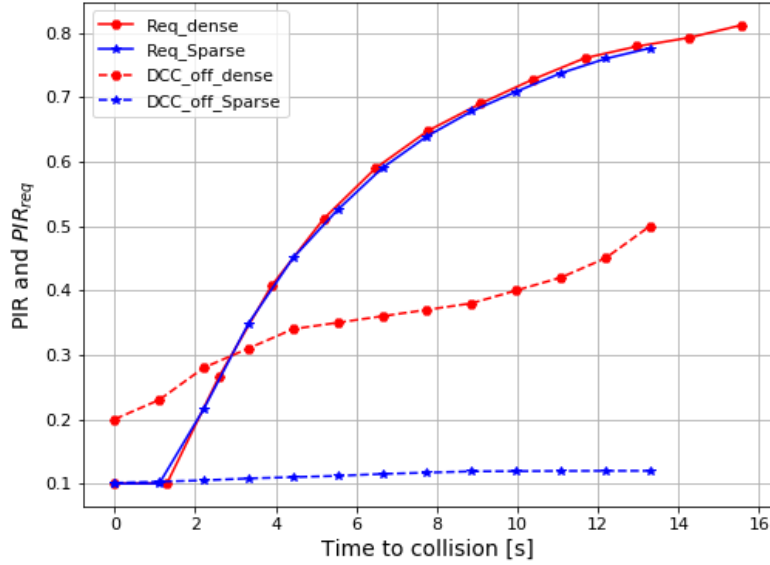


Figure 5.6: Comparing performances of Reactive DCC against the application requirement ( $PIR_{req}$ )

a dense traffic, the requirements are not satisfied especially when vehicles are very close to collision point ( $TTC < 2s$ ) which probably lead to dangerous situations. Fig. 5.6 shows that requirements are respected for dense and sparse densities only when vehicles are far from collision point ( $TTC > 2s$ ). In particular, when the traffic is dense and vehicles are approaching the junction point, the PIR performances the algorithm may lead to car-to-car collisions.

## Conclusion

It is striking to see that the DCC-applied solution is performing worse than the default solution when we consider the application requirements. This suggests that we have to be very careful when we design such solutions. Indeed, we believe that the real need is developing a context-aware communication algorithm that knows the application requirement, and hence controls the communication parameters such that the application

requirement is always met.

## 5.3 Performance evaluation of impacts of RSU on collective perception

As shown from our analytical models described in chapter 3, a significant performance degradation in CPM transmission, particularly message success probability, can be observed in dense traffic conditions due to a large number of communicating entities (vehicles, RSU and so on) competing for the radio resource. Therefore, we are interested in confirming potential benefits of contributions of RSU to CPS by comparing message success probability, i.e. PDR, when CPMs are generated by both vehicles and RSU with the case where CPM is generated only by RSU.

### 5.3.1 System setting and performance metrics

Similar to our work in chapter 3, the 3-lanes highway (see Fig. 3.11) scenario is considered targeting four different density cases that are defined in [113]: sparse, medium, dense and extreme corresponding to 10, 22, 50, and 100 vehicles/km/lane, respectively. V-ITS-S and R-ITS-S generate CPMs at every 100 ms. The CPM size depends on the vehicle density as depicted in Fig. 3.13. The ITS G5 (IEEE 802.11p) technology is used as the V2X communication technology. When a RSU is available, it is equipped with sensors and ITS G5 technology. The perception models of the vehicle on-board and the roadside sensors are presented in [114]. These models have been designed to simulate detection of objects that are in the sensors' FOV. On the one hand, vehicles' on-board sensors model integrates an occlusion model, i.e., takes into account occlusion induced by the presence of other vehicles. On the other hand, roadside perception model does not integrate such an occlusion model because roadside sensors can be installed sufficiently high as depicted in Table 5.2. The following performance indicators are used:

- Number of objects per transmitted CPM: reveals the capacity of a CPM to include detected objects by local sensors. In this simulation study, as we did in chapter 4 where we describe the analytical model for V2V and I2V communications, we compare the number of objects included on a CPM generated by a vehicle against the number of objects generated by a RSU. Such a metric gives an overview about benefits of considering RSU for CPS contribution.
- Effective number of objects per transmitted CPM: is the number of objects that receivers are newly informed by a given CPM. Indeed, due to data redundancy issue, a same object may be detected and transmitted, and hence received, several times by different neighboring entities. Thus, it is essential to know the effective number of objects that a CPM generated by either a vehicle or RSU contains.
- Packet Delivery Ratio (PDR): measured for each pair of transmitter and receiver as the ratio between the number of received packets over the number of transmitted packets.

Table 5.2: Simulation parameters

Parameter	Value
Road length	1000m
Number of lanes	3 lanes
Vehicle density	10,22,50,100 vehicles/km/lane
Modulation rate	6 Mbps
RSU antenna height	3m
VEH antenna height	1.5m
RSU sensor coverage	150m (360°)
VEH sensor coverage	100m
Propagation model	Two-Ray
Transmission power	20dBm
Message generation rate	100ms
Penetration rate	100%



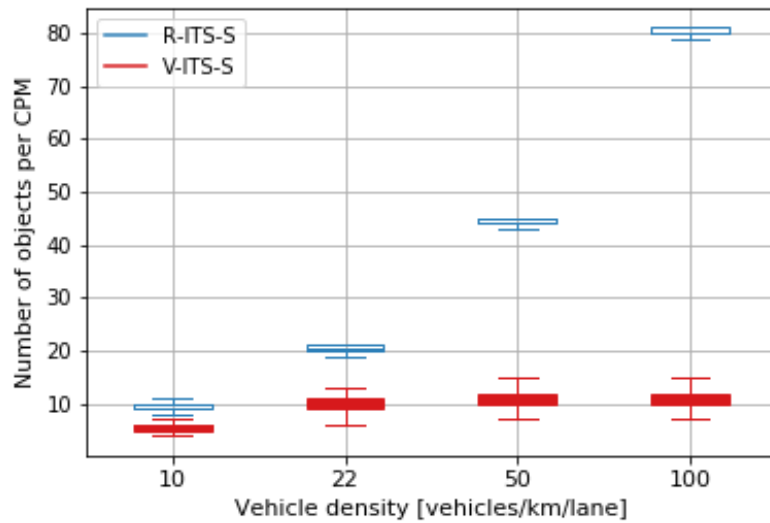


Figure 5.7: Number of objects per transmitted CPM function of vehicle density

### 5.3.2 Results

Fig. 5.7 compares the number of detected objects per CPM transmitted by R-ITS-Ss and V-ITS-Ss. The results clearly show that CPMs generated by R-ITS-Ss contain up to 8 times of more objects than CPMs generated by V-ITS-Ss. It should be noted that the result is quite similar to the analytical results depicted in Fig. 3.12.

We are now interested in the effective number of objects per CPM. Indeed, because an object can be detected by several vehicles and RSU, a receiver can be informed several times of this object during the CPM generation interval (100 ms). In this case, at the receiver, the effective number of this object is 1 regardless of several received CPMs informing the same object. Fig. 5.8 depicts the effective number of objects per received CPM when CPM is generated only at R-ITS-S (I2V-only) or only at V-ITS-S (V2V-only). The results reveal that, in V2V, the effective number of objects per CPM is very low (around 1) regardless of traffic density. In contrast, I2V presents much higher effective number of objects per CPM; the denser the traffic is the more effective is the individual CPM.

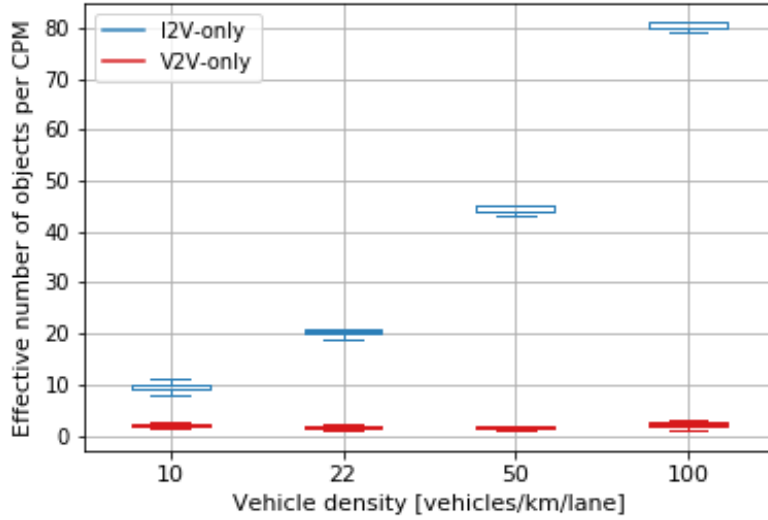


Figure 5.8: Effective number of objects per received CPM function of vehicle density

Now, we evaluate the average packet delivery ratio (PDR) for CPMs transmitted by vehicles and the RSU. PDR is calculated at each receiver for individual CPM transmitters (which are located within the communication range from the receiver) as the ratio of the number of received CPMs to the number of CPMs transmitted by the transmitter. Fig. 5.9 depicts the average PDR for different density cases. As expected, PDR degrades with the increase of the vehicle density. Furthermore, the PDR values at different densities are quite similar to the analytical results obtained in Fig. 3.14 confirming the correctness of the analytical model.

### 5.3.3 Conclusion

In conclusion, simulation results confirmed analytical results presented in chapter 3. Significant benefits of considering the presence of roadside infrastructure in the contribution to collective perception service are expected : RSU can include much more (up to 8) objects on its CPM compared to CPM transmitted by a vehicle. Also, success probability of message reception (PDR) when vehicles and RSU transmit CPMs degrades with the

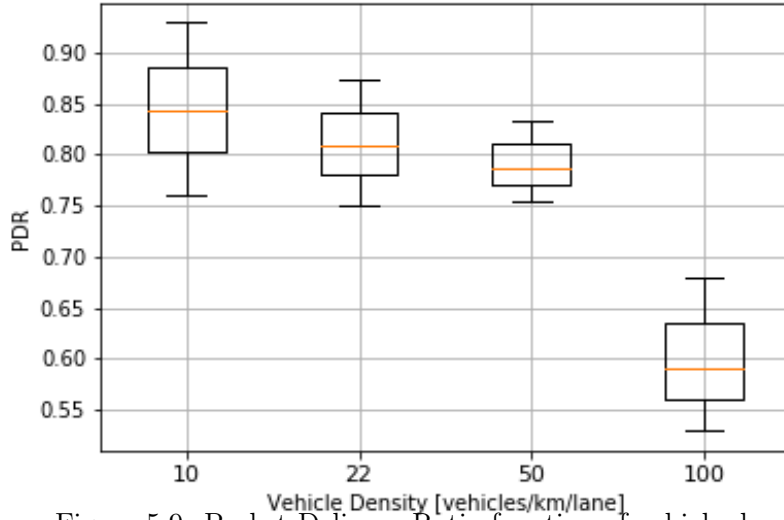


Figure 5.9: Packet Delivery Ratio function of vehicle density

increase of traffic density while it is maximized when only RSU transmit CPMs.

## 5.4 Performance evaluation of CPM dissemination control schemes

### 5.4.1 System setting and performance metrics

Our simulation study focuses on a dense traffic scenario in a multi-lanes highway road section with an average inter-vehicle distance of 20 m, i.e., a road density of 50 vehicles/km/lane. Then, we vary the penetration rate of connected vehicles equipped with IEEE 802.11p as the V2X communication technology (i.e., those have CP server/client modules): 20 %, 50 %, 75 % and 100 % . In order to evaluate the effectiveness of our proposed algorithms, the following performance metrics are used:

- Packet Delivery Ratio (PDR): Ideally, the proposed schemes should improve PDR, i.e., each transmitted packet is successfully received by the receiver by improving resource utilisation.

- Awareness rate: indicates the knowledge an ego vehicle has about nearby road users. It is measured as the ratio between the number of road users detected based on different perception means (on-board sensors, CPM or fusion of both sources) over the total number of road users situated in a target vicinity of the ego vehicle. Because the *Default* scheme periodically transmits the complete list of the perceived objects by the sensors (with a sufficient confidence), it tends to provide high awareness rate. The awareness rate may degrade in *Default* scheme if the channel is too congested. The objective of the proposed schemes is, hence, to provide at least the same level of awareness rate as *Default* scheme.
- Channel Busy Ratio (CBR): indicates the channel occupation, measured as the ratio of time during which channel is sensed as busy (the receive signal power exceeds a given threshold) over a given monitoring period. The objective of the proposed scheme is to reduce the CBR, while improving PDR and at least maintaining the awareness rate (of the *Default* scheme).

Finally, the proposed schemes in chapter 4 are assessed by comparing their performances against the *Default* scheme where a CPM may include all the objects perceived by the local sensors. They are evaluated with default parameters presented in Table 5.3. First, we consider threshold control function for *CBR-binary* and *CBR-selective* schemes is active when CBR is between 0.6 and 0.7 (respectively  $CBR_{min}$  and  $CBR_{max}$  value) and initial threshold in the number of object per CPM,  $InitThr_{binary}$ , is set to 0 with a step,  $\delta_{binary}$ , of 0.1 for CBR-binary scheme as the initial number of redundancy,  $InitThr_{selective}$ , for CBR-selective scheme is set to 5 with a step,  $\delta_{selective}$ , of 1. In this section, we considered a 4-lanes per direction highway scenario implemented in VEINS simulator as depicted Fig. 5.10.

Table 5.3: Simulation parameters.

Parameter	Value
Road length	1000 <i>m</i>
Number of lanes	4
Number of directions	2
Inter-car distance	20 <i>m</i>
Vehicle sensor coverage ( $D_{max}^v$ )	100 <i>m</i>
RSU sensor coverage ( $D_{max}^{RSU}$ )	150 <i>m</i>
RSU sensor FoV	360°
Lane width ( $w$ )	3 <i>m</i>
Vehicle length ( $d_{len}$ )	5 <i>m</i>
Vehicle width ( $d_w$ )	2 <i>m</i>
Data rate	6 Mbps
RSU antenna height	3 <i>m</i>
Vehicle antenna height	1.5 <i>m</i>
Propagation model	Two-Ray
Transmission power	20 dBm
$(InitThr_{binary}, \delta_{binary})$	(0, 1)
$(InitThr_{selective}, \delta_{selective})$	(5, 0.1)
$(CBR_{min}, CBR_{max})$	(0.6, 0.7)

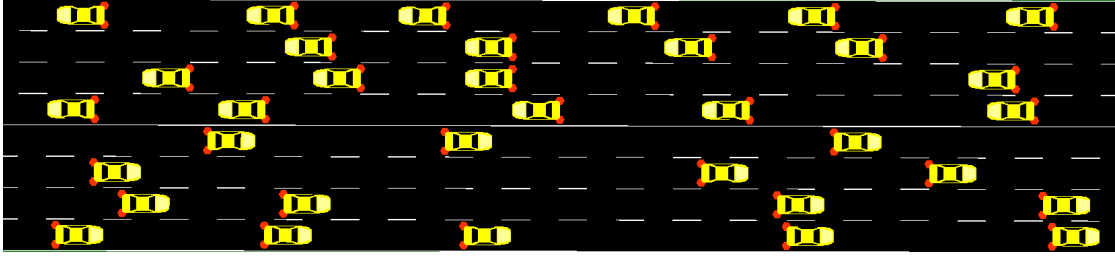


Figure 5.10: Simulated scenario for CPM content selection schemes

#### 5.4.2 Evaluation of *Infra-selective* scheme

As described in the previous chapter, *Infra-selective* scheme selects CPM contents (perceived objects) by considering if the contents have been already announced by a RSU. Fig. 5.11 compares the CBR performances of the scheme against Default scheme. As the results show, the channel usage can be improved if vehicles reduce CPM redundancy particularly for the contents that have been provided by the infrastructure.

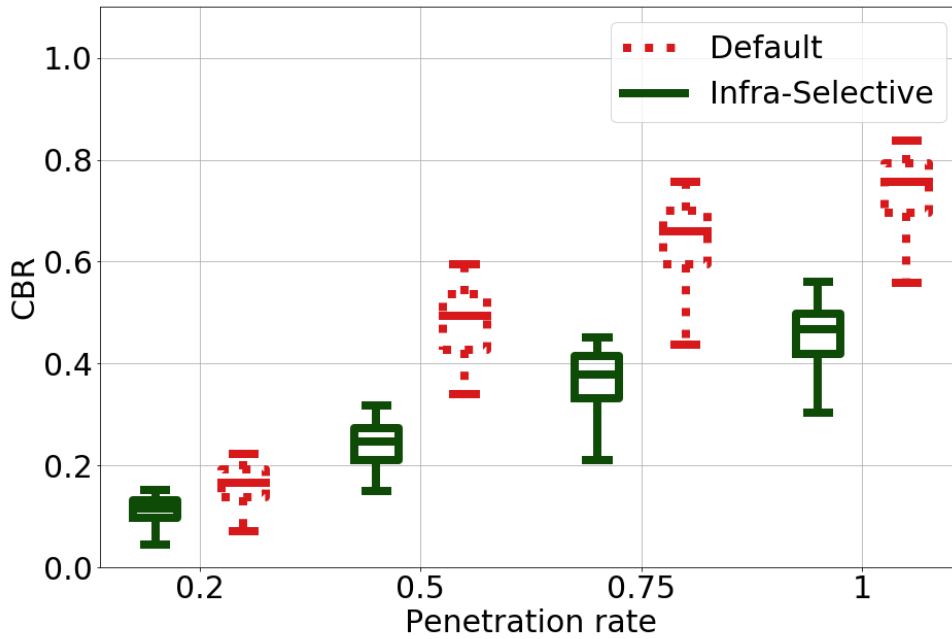


Figure 5.11: Comparing CBR between Infra-Selective and Default algorithms

Fig. 5.12 compares the PDR performances of *Infra-selective* and Default schemes. As can be seen, because the *Infra-selective* sends shorter CPMs it provides the improved PDR particularly for higher penetration rate. Finally, Fig. 5.13 shows that *Infra-selective* scheme could provide the slightly improved awareness rate compared to the Default scheme. This is a very positive result especially because it is obtained with the improved channel utilisation and PDR performances.

To conclude, availability of RSU is beneficial to reduce channel occupancy and hence improves successful reception of messages, i.e. PDR. Also, awareness rate is slightly better than *Default* scheme.

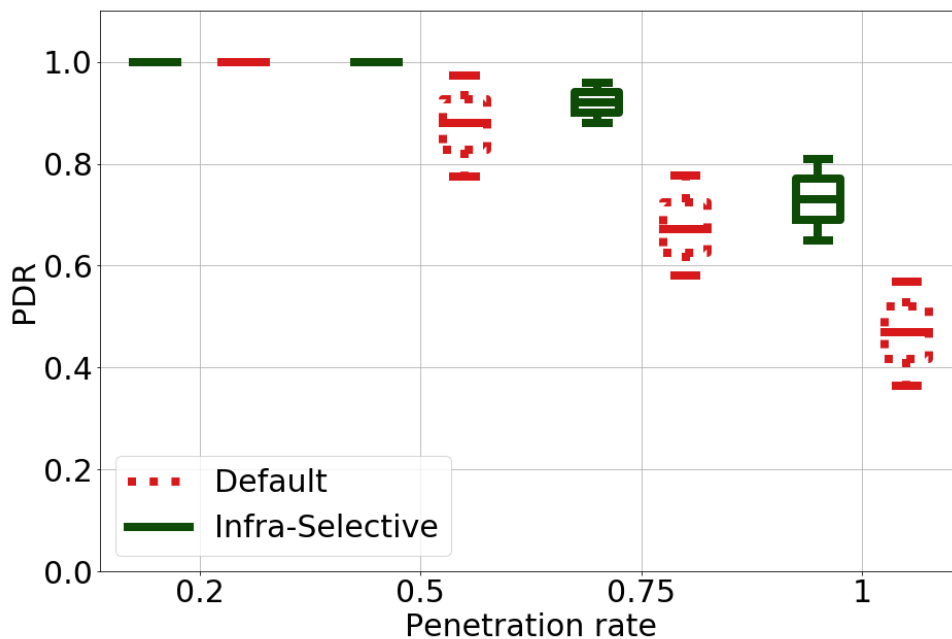


Figure 5.12: Comparing PDR between Infra-Selective and Default algorithms

### 5.4.3 Evaluation of *CBR-Binary* and *CBR-selective* schemes

Fig. 5.14 shows the PDR performances of the schemes. As expected, the higher the penetration rate, the lower PDR is, especially for the *Default* scheme. When the penetration rate is greater than 0.75%, both the *CBR-binary* and *CBR-selective* schemes perform better than the *Default* scheme. This can be explained as in these conditions, the proposed algorithms can sense the degradation of channel resource availability and control CPM's transmission opportunity or contents. We notice that median PDR value can be maintained above 75% even in the highest-load scenario, i.e. 100% of penetration rate. This clearly indicates the benefit of the proposals in improving communication reliability.

Fig. 5.15 illustrates the awareness rates of the three schemes. First of all, we can notice that, regardless of the scheme, the awareness rate increases with the increase of

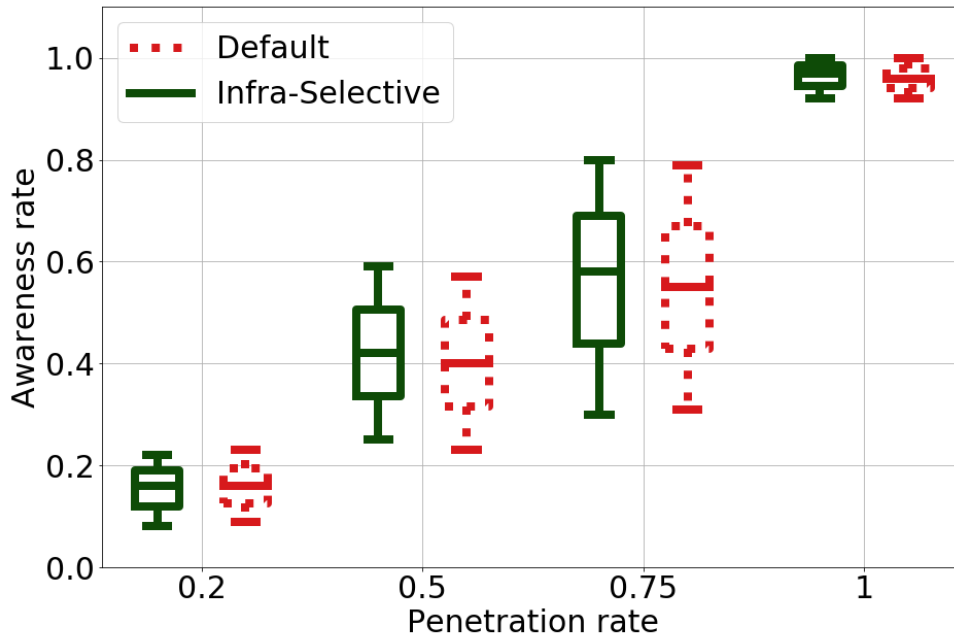


Figure 5.13: Comparing awareness rate between Infra-Selective and Default algorithms

the penetration rate. This is an expected behavior because, in low penetration rate scenario, vehicles have to rely mainly on their on-board sensors, which cover a small part of their surrounding environment, and hence they have low awareness rate. On the other hand, for high penetration rates, higher number of connected vehicles contribute in building collective perception, extending perception coverage, consequently increasing the awareness rate. Moreover, the figure confirms that *CBR-binary* and *CBR-selective* schemes have similar performances with the *Default* scheme.

Fig. 5.16 shows the CBR performances of the schemes. As the figure shows, in *CBR-binary* and *CBR-selective*, CBR remains below 0.6 even when the penetration rate is greater than 0.75% . The *CBR-selective* scheme tends to show even lower CBR, conceivably, because it reduces the CPM packet size.

In conclusion, the simulation results show that, in comparison to the *Default* scheme



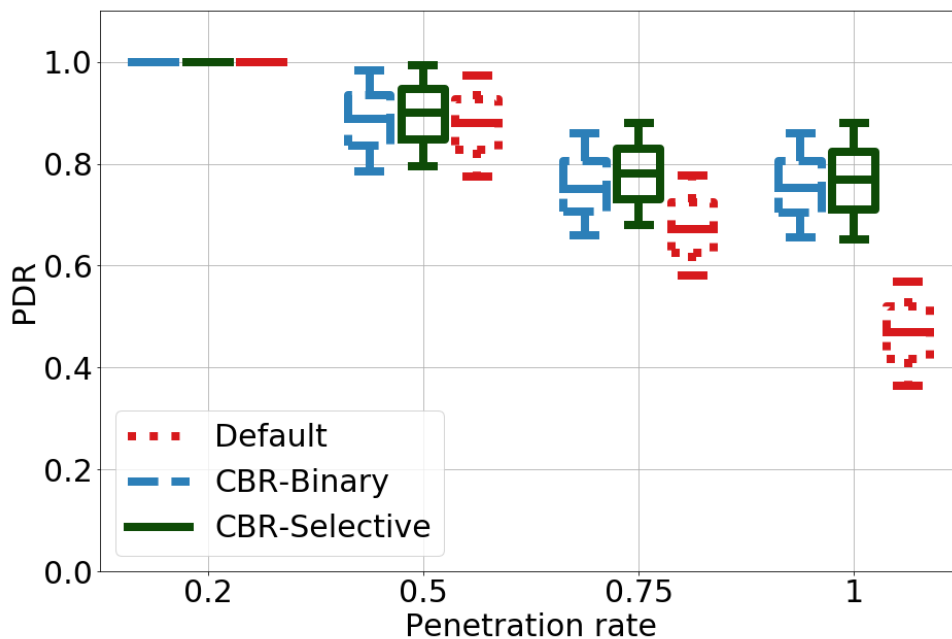


Figure 5.14: Comparing PDR of CBR-Selective, CBR-Binary and Default algorithms

that does not control CPM contents (i.e., periodically broadcasts the complete list of the perceived objects), both the schemes, *CBR-binary* and *CBR-selective*, improve packet delivery ratio (PDR) and reduce CBR while offering the same level of awareness rate as the *Default* scheme. Particularly, the results of CBR-selective show that it is possible to maintain the awareness rate with lower resource consumption (up to 30% of CBR reduction).

#### 5.4.4 Evaluation of *CBR&Infra selective* scheme

Fig. 5.17 compares the PDR performance of the *CBR&Infra selective* and *Default* schemes. The figure clearly shows that PDR is nearly 100% in all the scenarios for *CBR&Infra selective* scheme, providing up to 60% of improvement in comparison to the *Default* scheme. Indeed, we have shown in our previous work [7] that the presence of a

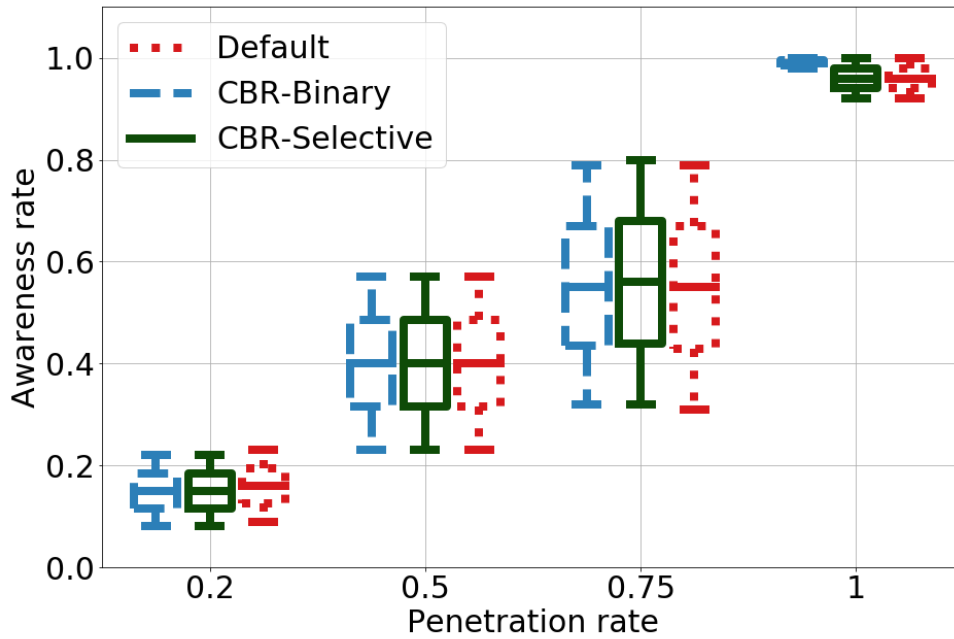


Figure 5.15: Comparing awareness rate of CBR-Selective, CBR-Binary and Default algorithms

roadside infrastructure can positively impact the CPM performance. Therefore, as fewer entities are sending data packets when RSU takes over vehicles for CPM transmission, higher PDR is observed, indicating more reliable communication.

Fig. 5.18 shows that awareness rate of the schemes. As we can see the proposed approach is very similar to the performances obtained with the *Default* scheme. Consequently, collective perception performances are maintained with the proposed approach while communication performance are largely improved.

Finally, reduced channel usage is confirmed by Figure 5.19 showing that, in the presence of a RSU, median CBR value remains below 40 % which represents a decrease of 30 % at 100 % penetration rate for CPM transmission.

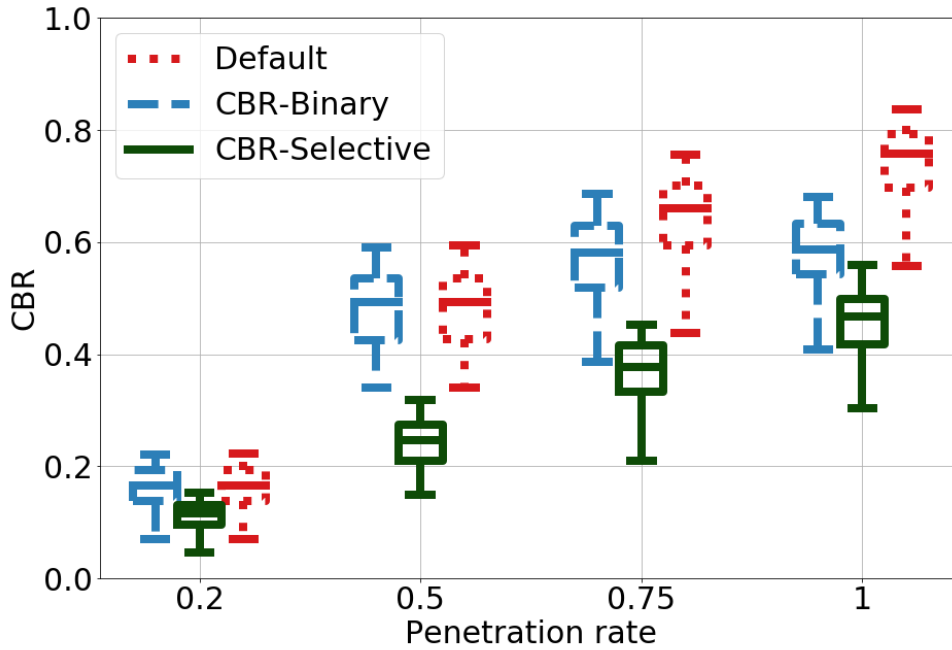


Figure 5.16: Comparing CBR of CBR-Selective, CBR-Binary and Default algorithms

#### 5.4.5 Conclusion

To summarise, *CBR&Infra selective* scheme overcomes the *Default* algorithm and presents improved results in terms of radio resource utilisation and packet delivery ratio. Indeed, the results confirm that solutions that control/select CPM contents tend to show improved performances. Furthermore, when a roadside infrastructure is available, relying on such an entity broadcasting CPMs has a major impact on improved resource utilisation and PDR while still providing a sufficient level of situation awareness. This is because, in the proposed *CBR&Infra selective* scheme, vehicles remove contents from their CPM, if the same contents have been announced by an RSU, resulting in fewer and shorter CPM packets being transmitted in the channel and hence individual CPMs have larger informative quantity. Therefore, by adapting CPM transmission to the context, in particular by replacing V2V communication by I2V communication seems to be greatly

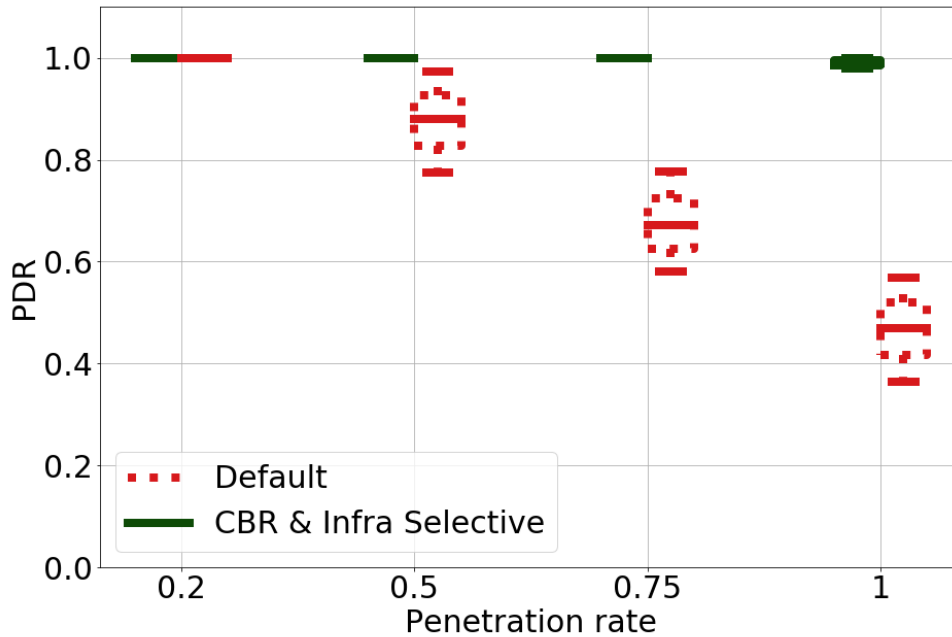


Figure 5.17: Comparing PDR of CBR & Infra Selective and Default algorithms

beneficial.

Nevertheless, the *CBR&Infra selective* scheme looks at two types of contexts, CBR and infrastructure availability, (see Table 5.4), which may lead to more complex system with potentially higher processing overhead. In contrast, despite its lowest expected performances compared to *CBR-selective* and *CBR&Infra selective*, *CBR-Binary* probably the easiest to implement, because it simply decides whether or not to transmit the whole list of perceived objects based on the measured CBR.

#### 5.4.6 Discussion

Situation awareness and packet delivery ratio have been the main key performance indicators used in the literature to assess reliability of CPM generation approaches [40, 41, 44]. Thus, we believe that they are the primary indicators for the evaluation of collective per-

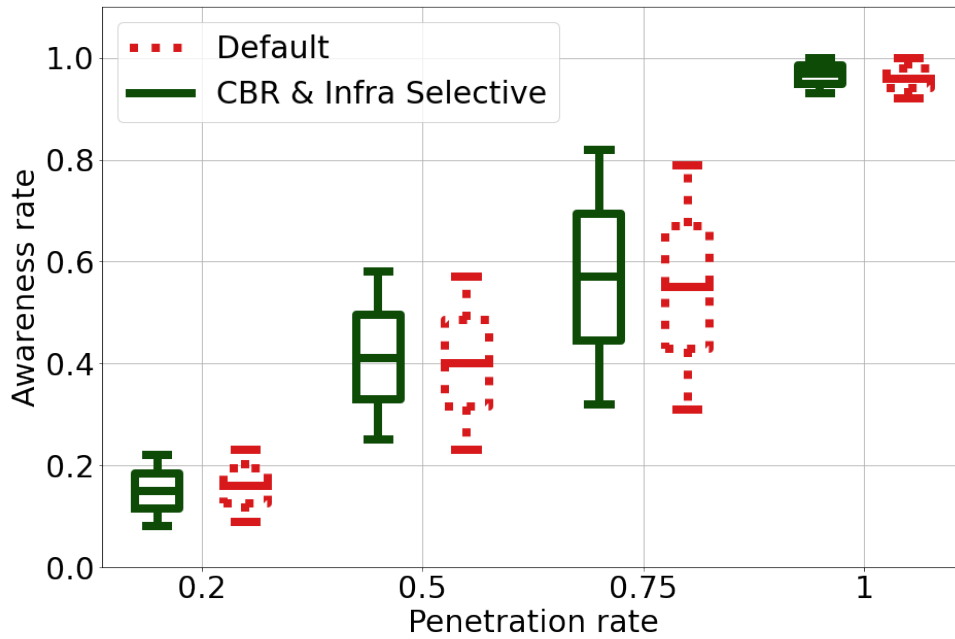


Figure 5.18: Comparing Awareness rate of CBR & Infra Selective and Default algorithms

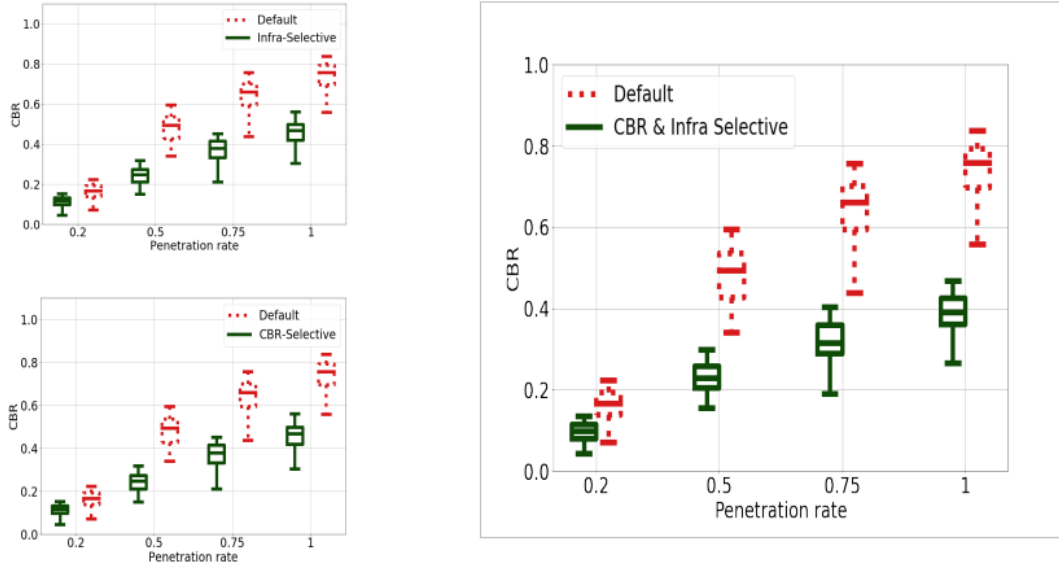


Figure 5.19: Comparing CBR of CBR & Infra Selective and Default algorithms

Table 5.4: CPM generation and content selection algorithms.

	CBR-Binary	CBR-Selective	CBR & Infra Selective
<i>Number of used contexts</i>	1	1	2
<i>Expected performances</i>	low	medium	high
<i>Parameters to be controlled</i>	<i>ThresholdBinary</i>	<i>ThresholdSelective</i>	<i>ThresholdSelective</i>

ception performances. Additionally, metrics such as payload size, CBR, detected object redundancy can complement the above mentioned indicators for collective perception service evaluation [40, 43]. Other researchers demonstrated, similarly to our work, that awareness rate can be maintained at a high level while CPM generation is controlled from external factors to minimize impacts on the communication channel [44, 40]. By studying multiple CPM generation and data content selection schemes, this work highlights major factors (or contexts) which influence reliability of collective perception service and how to take them into consideration for intelligent message dissemination.

First, it appears clearly from our results that controlling CBR is essential to maintain channel availability, thus, providing higher reliability. Second, when an infrastructure is available, it should take message dissemination over the vehicles as it benefits from better capacity in terms of communication and perception coverage. Therefore, *CBR&Infra selective* schemes outperform the other approaches presented in this chapter, especially in dense scenarios. Complementary, as sparse scenarios are less subject to degradation of communication reliability, a higher degree of data redundancy could be accepted. This would improve other performance indicators such as object localization accuracy. Indeed, in such scenarios, higher velocities of road users may degrade this indicator due to high dynamics of the environment. Besides, evaluating object localization error is essential for the validation of automated systems, e.g. CAV, and has been considered in [44] where measurement errors are simulated. In our work, this aspect could not be

evaluated, however, it will be relevant for future research especially when targeting real world experimentation.

## 5.5 Conclusion

In this chapter, we presented evaluation metrics and simulation setup for different simulation evaluations. We first conducted simulations to evaluate different CAS strategies and showed that Periodic-CAM and Reactive-DCC cannot meet application requirements in dense scenarios. We also simulated the impacts of infrastructure availability, i.e. environmental context, on CPS and confirmed the results obtained from analytical models: RSU are beneficial for CPS in terms of number of objects per CPM as well as PDR especially when vehicle density increase. Finally, we evaluated the proposed CPM content selection schemes. We observe that *infra-selective* scheme performs better than default scheme in terms of radio resource utilisation and PDR. We showed also that *CBR-binary* and *CBR-selective* schemes, by taking into account CBR, could successfully improve PDR and reduce radio resource utilisation while maintaining the awareness rate of the *Default* scheme. Finally, the results show that *CBR&Infra selective*, the hybrid algorithm combining radio resource context and infrastructure availability, presents the best performance in terms of radio resource utilisation and packet delivery ratio while maintaining the awareness rate of the *Default* scheme.

# Chapter 6

## Conclusion and perspectives

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## 6.1 General conclusion

We have been witnessing significant efforts on designing, developing and deploying C-ITS systems for improved road safety. The main objective is to avoid/reduce accidents by warning the driver/vehicle about dangerous situations. Without C-ITS, vehicles need to perceive their environment via on-board sensors, e.g. radar, lidar, cameras. However, a perception system that relies on only local observations is not enough for complex driving manoeuvres, e.g. lane changing in urban areas or lane merging on a highway, due to sensor inaccuracy or limited field of view. In C-ITS, an extended global perception is built based on cooperation between all vehicular entities (vehicles, road side infrastructure, traffic management centers, etc). Indeed, augmented perception relies on the exchange of multiple messages, i.e. Cooperative Awareness Message (CAM) and Collective Perception Message (CPM), to complement the local perception and assess state variables of other road users. Because applications of C-ITS have to operate in heterogeneous conditions, in terms of environmental situations (e.g. road types, weather conditions) and technologies (e.g. communication media, network infrastructure), we believe that context-awareness can be considered as a key aspect to intelligently control protocols and services, particularly CAS and CPS and ensure making adequate decisions according to each traffic situation.

In this thesis, we first identified context aware system architecture derived from the ETSI reference architecture and implements context awareness on the management layer following the three phases of context cycle: context acquisition, context reasoning and system control. Then, targeting collision avoidance, we defined contexts that we consider the most important for such applications. The first type of context is the application requirement that should be satisfied by the communication systems so that they fulfil their role in supporting collision avoidance. Indeed, although CAM/CPM generation strategies focus on improving communication performance and/or radio resource utili-

sation, they do not know the application requirements and consequently, their impacts on application performances. The second type of context is resource availability which consists on measuring channel occupancy using CBR in order to manage shared resources within all vehicular nodes. In fact, such a contextual factor is essential as it supports the control of the transmission reliability of messages and adjusts generation rates according to channel occupancy. Finally, apart from application requirement and radio resource management contexts, external factors such as environmental conditions in terms of road layout, road infrastructure availability, traffic density, etc should be considered. Such a context impacts the transmitting entity (either a vehicle, a RSU, a MEC device, etc..) as well as the rate of message transmission. We have been particularly interested in the infrastructure availability, especially the availability of RSUs equipped with sensors that provide higher benefits in providing CPS.

Once contexts are identified, we worked on modeling contextual data that support collision avoidance application. We defined application requirements in terms of PDR and PIR derived from collision probability. High reliability is the paramount challenge for such applications as they rely on exchange of mobility data informing the presence of surrounding entities. We showed that existing CAM generation strategies those of DCC solutions do not meet application requirements. Consequently, communication parameters such as message generation rate and message content selection should be adjusted considering different context so that requirements are always met.

Then, we put a focus on external context, i.e. environment context, which represents the availability of RSU and its benefits for CPM generation. The proposed analytical model as well as simulation study showed that a CPM generated by a RSU may include 8 times more objects than a CPM generated by a vehicle. Indeed, positive impacts about improving PDR, decreasing CBR and at least keeping the same level of awareness rate are confirmed when RSU contribute to CPS. This allow I2V communication replace V2V communication for the road sections where RSUs are deployed.

After modeling contextual data, we interested in CPS adjusting communication parameters including CPM generation rate and content selection. To this end, we designed context aware CPM content selection schemes that take into account radio resource context or/and infrastructure availability context. First, in *Infra-Selective*, where availability of the infrastructure is considered as an environmental context, a vehicle fills its CPM with an object if and only if the latter is not perceived by the RSU. Such a scheme allows vehicles to reduce the number of objects in their CPMs considering RSU contributions to collective perception. Second, when considering resource availability context, in *CBR-binary*, the CPM server transmits the whole list of objects if only if the number of objects that have been detected by only the ego-vehicle exceeds a threshold, determined from the current channel busy ratio (CBR). In comparison, the *CBR-selective* scheme fills outgoing CPMs only with the objects that have been detected by less than a given number of neighbors: a threshold value determined from the current CBR. Finally, *CBR&Infra selective* scheme, which takes into account not only radio resource utilisation but also if the objects have been announced by a roadside infrastructure. The latter enhances the intelligent control of communication parameters (i.e. CPM generation rate and content selection) since it adapts them according to two contexts: radio resource utilisation and the presence of RSU that contributing to collective perception.

The performances of the proposed schemes are evaluated by VEINS network simulator using several performance indicates: PDR, CBR and awareness rate. The results showed that context aware schemes perform better than default scheme in terms of resource utilisation (reduction on CBR up to 40% for *Infra-selective* scheme), message success probability (gain up to 40% in dense traffic for *Infra-selective* scheme and 50% for *CBR-Selective* scheme) while maintaining at least the same level of awareness rate provided by *Default* scheme. Moreover, we confirmed that our multi context-aware scheme *CBR&Infra selective* outperforms the default scheme as well as the proposed context aware schemes in terms of the evaluated metrics. Particularly, it provides almost 100%

of PDR regardless traffic density, and hence it satisfies the application requirement, obtaining its role of supporting road safety applications.

## 6.2 Perspectives

Although the objectives of this thesis are achieved and the results are satisfying, the following additional tasks need to be fulfilled.

- Implementation of the proposed schemes in a V2X testbed platform and demonstration of its effectiveness by real-world experimentation. In our future work, we intend to integrate the proposed context aware schemes in VEDECOM's hybrid V2X communication platform that consists of vehicles, roadside sensors (lidars, cameras), and infrastructure capable of communicating using different communication technologies (ITS-G5, LTE, VLC and etc).
- Security aspects should be taken into account. Indeed, although vehicular networks rely on the exchange of accurate and recent information, they are vulnerable to different attacks including those made by misbehaving nodes, which may transmit false information leading to potentially dangerous situations. Particularly, such internal attacks have a massive impact on collision avoidance applications which shall use exchanged data effectively so that road accidents are reduced/avoided. Therefore, we intend to integrate a misbehavior detection algorithm that checks information accuracy before executing CPM content selection.
- Based on the obtained insights and results of the current PhD work, we intend to contribute to the ETSI standardisation activities, particularly ETSI ITS TC WG1 and WG2. ETSI ITS TC WG1 focuses on applications and services. In WG1, we could propose our definition of collision avoidance application requirement and specifications of CPM content selection strategies. ETSI ITS TC WG2 is interested

in ITS communication architecture and cross layer. A contribution on context aware architecture can be made.

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