Universidade de Aveiro
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Marco Daniel Correia

Infraestrutura de beira de estrada para apoio a Sistemas Cooperativos e Inteligentes de Transportes

Roadside infrastructure to support Cooperative Intelligent Transportation Systems

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Dissertação apresentada à Universidade de Aveiro para cumprimento dos requisitos necessários à obtenção do grau de Mestre em Engenharia de Eletrónica e Telecomunicações, realizada sob a orientação científica do Doutor Joaquim José de Castro Ferreira, Professor Coordenador da Escola Superior de Tecnologia e Gestão de Águeda da Universidade de Aveiro, do Doutor José Alberto Gouveia Fonseca, Professor Associado do Departamento de Eletrónica, Telecomunicações e Informática da Universidade de Aveiro, e do Doutor João Miguel Pereira de Almeida, Investigador do Instituto de Telecomunicações.

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o júri / the jury

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Palavras Chave

ITS, Infraestrutura rodoviária, Comunicações veículares, Perceção coletiva, ITS-G5, Radar, Comunicações móveis.

Resumo

A crescente necessidade de mobilidade em paralelo com a evolução da indústria automóvel e com a massificação do uso de meios de transportes pessoais, têm vindo a amplificar alguns problemas dos transportes rodoviários, tais como a segurança e o congestionamento do tráfego. Para mitigar estas questões, a evolução das tecnologias de comunicação cooperativas e dos sistemas autónomos é vista como uma potencial solução para ultrapassar limitações dos condutores e do horizonte de perceção dos sensores veículares. Comunicações de curto alcance, tais como Veículo-a-Veículo ou Veículo-a-Infrastrutura (ETSI ITS-G5), em conjunto com comunicações móveis de longo alcance (LTE,5G) e mensagens padrão, emergem como soluções viáveis para amplificar todos os beneficios que tecnologias independentes podem trazer para o ambiente rodoviário, cobrindo um grande leque de aplicações e casos de uso da estrada. Em conformidade com o trabalho de padronização da *European Telecommunications Standards Institute*, esta dissertação descreve a implementação do serviço de perceção coletiva, numa infrastrutura rodoviária real, para suporte a manobras de veículos autónomos e para fornecer informações aos operadores de estradas. Este trabalho foca-se na construção de mensagens de perceção coletiva a partir de informação gerada por radares de classificação de tráfego (instalados no âmbito do projeto PASMO) para disseminação local usando a tecnologia rádio ETSI ITS-G5 e criando um canal de comunicação redundante entre a infraestrutura rodóviaria e um centro de controlo de tráfego localizado no Instituto de Telecomunicações - Aveiro, usando para isso: redes móveis, ligações rádio ponto a ponto e fibra ótica. O conteúdo destas messagens é mostrado ao utilizador através de uma aplicação móvel. O serviço é ainda melhorado, tendo-se para tal desenvolvido um algoritmo de otimização de disseminação das mensagens, tendo em vista melhorar a eficiência do canal de transmissão em cenários mais exigentes. Os resultados dos testes experimentais efetuados revelaram que o tempo de atraso entre o evento de produção de uma mensagem de perceção coletiva e a receção por outra estação ITS, usando comunicações ITS-G5, se encontra dentro dos limites definidos pelos padrões da ETSI. Além disso, o algoritmo para disseminação de mensagens também mostrou aumentar a eficiência do canal de rádio, limitando o número de objetos disseminados pelas mesmas. Assim, o serviço de perceção coletiva desenvolvido poderá ser uma ferramenta valiosa, contribuindo para o aumento da segurança rodóviaria e para a disseminação da utilização dos sistemas cooperativos de transporte inteligente.

Keywords

ITS, Road infrastructure, Vehicular communications, Collective perception, ITS-G5, Radar, Cellular communications.

Abstract

The growing need of mobility along with the evolution of the automotive industry and the massification of the personal vehicle amplifies some of the road-related problems such as safety and traffic congestion. To mitigate such issues, the evolution towards cooperative communicating technologies and autonomous systems is considered a solution to overcome the human physical limitations and the limited perception horizon of on-board sensors. Short-range vehicular communications such as Vehicle-to-Vehicle or Vehicle-to-Infrastructure (ETSI ITS-G5) in conjunction with long-range cellular communications (LTE,5G) and standardized messages, emerge as viable solutions to amplify the benefits that standalone technologies can bring to the road environment, by covering a wide array of applications and use cases. In compliance with the standardization work from European Telecommunications Standards Institute (ETSI), this dissertation describes the implementation of the collective perception service in a real road infrastructure to assist the maneuvers of autonomous vehicles and provide information to a central road operator. This work is focused on building standardized collective perception messages (CPM) by retrieving information from traffic classification radars (installed in the PASMO project) for local dissemination using ETSI ITS-G5 radio technology and creating a redundant communication channel between the road infrastructure and a central traffic control centre, located at the Instituto de Telecomunicações - Aveiro, taking advantage of cellular, point-to-point radio links and optical fiber communications. The output of the messages are shown to the user by a mobile application. The service is further improved by building an algorithm for optimizing the message dissemination to improve channel efficiency in more demanding scenarios. The results of the experimental tests showed that the time delay between the production event of the collective perception message and the reception by other ITS stations is within the boundaries defined by ETSI standards. Moreover, the algorithm for message dissemination also shows to increase radio channel efficiency by limiting the number of objects disseminated by CPM messages. The collective perception service developed and the road infrastructure are therefore, a valuable asset to provide useful information for improving road safety and fostering the deployment of intelligent cooperative transportation systems.

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Acronyms

3GPP	Third Generation Partnership Project
4G	Fourth Generation Mobile System
5G	Fifth Generation Mobile System
ARP	Address Resolution Protocol
ASN.1	Abstract Syntax Notation One
AV	Automated Vehicles
BSA	Basic Set of Applications
BSC	Base Station Controller
BSS	Basic Service Set
BSSID	Basic Service Set Identification
BTP	Basic Transport Protocol
BTS	Base Transceiver Station
C-V2X	Cellular-V2X
CA	Cooperative Awareness
CAM	Cooperative Awareness Message
CAN	Controller Area Network
CBR	Channel Busy Ratio
CCAM	Cooperative, Connected and Autonomous Mobility
CDC-ECM	Communications Device Class – Ethernet Control Module
CEPT	European Conference of Postal and Telecommunications Administrations
C-ITS	Cooperative Intelligent Transport Systems
CP	Collective Perception
CPM	Collective Perception Messages
CPS	Collective Perception Service
CRDA	Central Regulatory Domain Agent
CSMA/CA	Carrier Sense Multiple Access with Collision Avoidance
D2D	Device to Device
DCC	Decentralized Congestion Control
DE	Data Elements
DEN	Decentralized Environmental Notification
DENM	Decentralized Environmental Notification Message
DF	Data Frames
DFS	Dynamic Frequency Selection
E-UTRA	Evolved Universal Terrestrial Radio Access
E-UTRAN	Evolved Universal Terrestrial Radio Access Network
EDCA	Enhanced Distributed Coordination Access
EEPROM	Electrically Erasable Programmable Read-Only Memory
eMBB	enhanced Mobile Broadband
eNB	Evolved Node B
EPC	Evolved Packet Core
EPS	Evolved Packet System
ETSI	European Telecommunications Standards Institute
EU	European Union
FDD	Frequency Division Duplexing
FMCW	Frequency Modulated Continuous Wave
FOTA	Firmware Over The Air
GPC	GNSS positioning correction
GPIO	General Purpose Input/Output
GPS	Global Positioning System
GSM	Global System for Mobile Communications
gNB	generation Node-B
GNSS	Global Navigation Satellite System
HMI	Human Machine Interface
HSPA	High Speed Packet Access
I2I	Infrastructure-to-Infrastructure
I2V	Infrastructure-to-Vehicle
IEEE	Institute of Electrical and Electronics Engineers
IMAGinE	Intelligent Maneuver Automation
IMT-Advanced	International Mobile Telecommunications Advanced
IP	Internet Protocol
IT	Instituto de Telecomunicações - Aveiro
ITS	Intelligent Transport Systems

ITSC	Intelligent Transport System Communications
ITS-S	ITS Station
ITU	International Telecommunication Union
IVI	Infrastructure to Vehicle Information
IVIM	Infrastructure to Vehicle Information Message
LAM	Lane change Advice Message
LAN	Local Area Network
LDM	Local Dynamic Map
LiDAR	Light Detection And Ranging
LLC	Logical Link Control
LOS	Line of Sight
LTE	Long Term Evolution
M2M	Machine to machine
MAC	Medium Access Control
MAPEM	Map Extended Message
MAVEN	Managing Automated Vehicles Enhances Network
MBIM	Mobile Broadband Interface Model
mBm	millibel-milliwatts
MCM	Maneuver Coordination Message
MCS	Maneuver Coordination Service
MIB	Management Information Base
MIMO	Multiple Input Multiple Output
mPCIe	mini Peripheral Component Interconnect express
MQTT	Message Queuing Telemetry Transport
mSATA	mini Serial Advanced Technology Attachment
NR	New Radio
NTP	Network Time Protocol
OBU	On-Board Unit
OCB	Outside the Context of a BSS
OER	Octet Encoding Rule
OFDM	Orthogonal Frequency Division Multiplexing
OSI	Open Systems Interconnection
PC	Personal Computer
PCI	Protocol Control Information
PDU	Packet Data Unit
PDR	Packet Delivery Ratio
PHY	Physical Layer
PTP	Precision Time Protocol
QoS	Quality of Service
RADAR	Radio Detection and Ranging
RAN	Radio Access Network
RAT	Radio Access Technologies
RHW	Road Hazard Warning
RLAN	Radio Local Area Network
RLT	Road and Lane Topology
RNC	Radio Network Controller
RSU	Roadside Unit
RTCMEM	Radio Technical Commission For Maritime Services Extended Message
SAE	System Architecture Evolution
SDU	Service Data Unit
SNAP	SubNetwork Access Protocol
SPATEM	Signal Phase And Timing Extended Message
SREM	Signal Request Extended Message
SSD	Solid State Drive
SSEM	Signal request Status Extended Message
SSH	Secure Shell
SSID	Service Set Identification
TCP	Transmission Control Protocol
TLC	Traffic Light Control
TLM	Traffic Light Maneuver
TMC	Traffic Management Configurator
TDC	Transmission Datarate Control
TPC	Transmission Power Control
TRC	Transmission Rate Control
TransAID	Transition Areas for Infrastructure-Assisted Driving
UART	Universal Asynchronous Receiver-Transmitter
UE	User Equipment
UHD	Ultra High Definition
UMTS	Universal Mobile Telecommunications System
UPER	Unaligned Packed Encoding Rule
URLLC	Ultra Reliable and Low Latency Communications
USB	Universal Serial Bus
USIM	Universal Subscriber Identity Module
UTC	Universal Coordinated Time
V2I	Vehicle-to-Infrastructure
V2N	Vehicle-to-Network
V2R	Vehicle-to-Vulnerable Road User
V2V	Vehicle-to-Vehicle
V2X	Vehicle-to-Everything
VANET	Vehicular Ad hoc Network
VoIP	Voice over IP
VPN	Virtual Private Network
VRU	Vulnerable Road User
XER	Extensible Markup Language Encoding Rule
XML	Extensible Markup Language
WAN	Wide Area Network
WAP	Wireless Protected Access 2
WEP	Wired Equivalent Privacy
WiFi	Wireless Fidelity
WLAN	Wireless Local Area Network
WWW	World Wide Web

CHAPTER 1

Introduction

The first chapter introduces the theme of the present dissertation. It starts with the motivation that analyses the theme from an environmental, economical, social, and technological point of view, how it could affect the road environment and all benefits associated with it. The chapter continues with the purpose and objectives of the document and ends with a brief overview of the following chapters that make this dissertation.

1.1 Contextualization

Transportation activity has been increasing in the past years in every country of the European Union (EU) [1] and will continue to grow, indicating that more citizens are getting personal cars and more goods are moving between countries [2] reflecting the evolution of online consuming services. According to the European Automobile Manufacturers, the automotive sector employs 13.8 million workers representing 6.1 % of total EU employment, claiming to be one of the biggest producers of motor vehicles in the world [3], meaning that, this area represents a substantial slice of EU employability and also that transport services and vehicle manufacturers must keep up with the sector's growth and society demand, not only in an economical point of view (more and cheaper cars), but also in a technological point of view, so they can offer the most comfortable and safest experience to the driver.

Despite the efforts by manufacturers in offering more advanced and effective safety triggers in their vehicles, road fatalities are still a big concern for society, not exclusively for car drivers, but also for every road user. In 2018, more than 23 thousand people died [4] in the EU, but also if we consider a world scenario it's more than a million deaths [5], resulting in millions of expenses in dealing with road accidents and all its consequences. Traffic congestion can also be a problem in a big-scale environment. Drivers spend a large amount of hours in traffic queues everyday and it is continuously increasing in big cities all over Europe [6]. This issue could be reflected into public health problems, economic costs, and environmental problems [7], diminishing the quality of life of citizens living in big metropolitan areas.

Combining all negative aspects of the road environment equates a need for the deployment of new technologies not only in vehicles but also in infrastructures. These emerging technologies should be able to communicate with each other to mitigate the driver's limitations like slow reaction times and limited line of sight, giving him the tools – or even do work for him - to become more aware of his surroundings and more capable of preventing dangerous situations. Making use of close-range and long-range communication technologies between vehicles or between vehicles and infrastructure, a connected environment could be achieved, creating a large network of vehicular communications and giving light to the term Intelligent Transport Systems (ITS) (figure 1.1) [8].

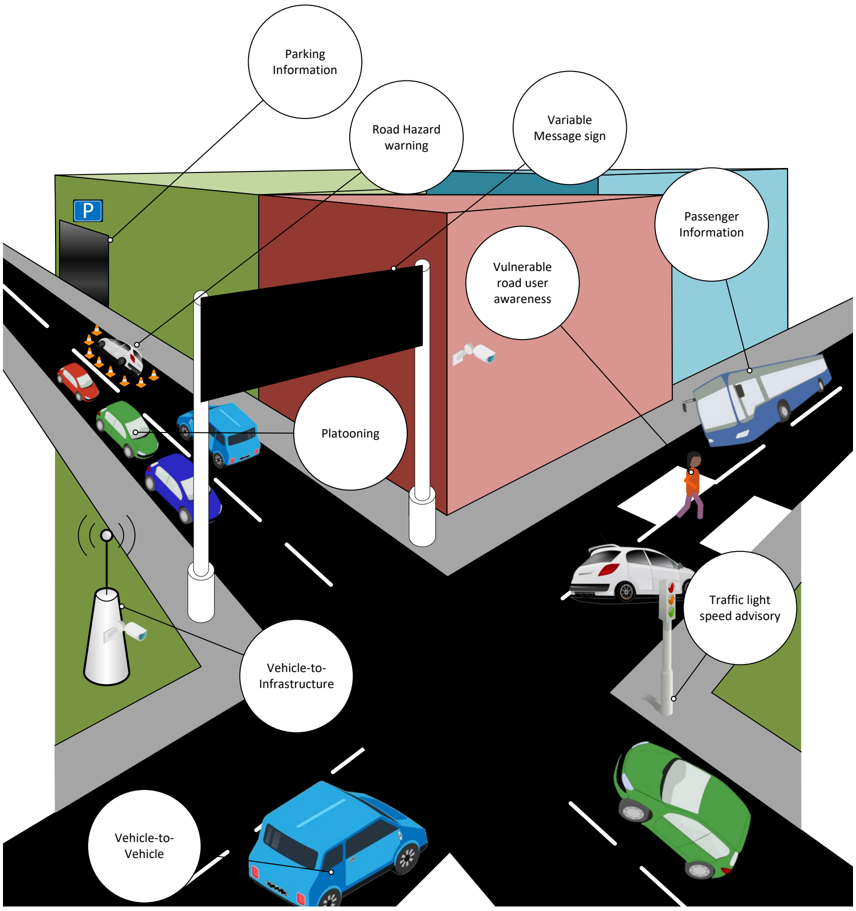

Figure 1.1: A large connected road environment

For this network to be reliable and up-to-date, a great and fast number of messages must be exchanged between all nodes inside the network in a dedicated band of the spectrum. These messages could disseminate important information such as vehicle dynamics and objects detected by each local sensorial system, providing more reliability and environmental perception for connected and/or automated vehicles. To achieve this, standards must be analysed and created to regulate traffic information. In the case of Europe, such standards are defined by the European Telecommunications Standards Institute (ETSI) [9], that among others, define the Collective Perception Service (CPS) that aims to share sensorial information detected by local sensors to the road environment.

Currently, many use cases are being tested like cross-border situations, lane merging or lane overtaking in different environments, where not only vehicles with communication capabilities are integrated, but also legacy vehicles which can not communicate with external nodes, creating a solid base for these technologies to emerge on real traffic scenarios.

1.2 PURPOSE

In compliance with the growing trend of modernization and sensorization of the road environment, to mitigate all associated risks and negative aspects, the main purpose of the work presented is to integrate traffic radars into the road infrastructure to collect auxiliary data to monitor and help Cooperative Intelligent Transport Systems (C-ITS) by increasing the level of perception in a road environment with a low penetration percentage of connected vehicles.

1.3 OBJECTIVES

For the work developed in this dissertation, the main objectives were the following:

- Implementation of the collective perception service into a system architecture based on the ETSI standards.
- Construction of collective perception messages based on the information provided by a traffic radar.
- Implementation of the radar's communication between the road infrastructure and a central office.
- Design and implementation of an algorithm for optimizing the collective perception messages dissemination.
- Integrate the visualization of the collective perception messages in a mobile application.

1.4 STRUCTURE OF THE DISSERTATION

The remainder structure of this dissertation is divided into five more chapters organized as follows:

- **Chapter 2: Fundamental Concepts -** Provides detailed information about the main concepts and topics associated with Intelligent Transport Systems. The chapter also presents a review of the literature directed to the theme of this dissertation.
- **Chapter 3: System Architecture -** Contextualizes the work of this dissertation and expose the architecture of the proposed system.
- **Chapter 4: Implementation -** Provides a detailed description of the work implemented.
- **Chapter 5: Tests and Results -** Presents, describe and discuss the tests performed to the implementation work and the subsequent results obtained.
- **Chapter 6: Conclusion and Future Work -** Evaluates the results obtained and provides insights for future work.

CHAPTER 2

Fundamental Concepts and state of the art

This chapter introduces some of the concepts present in the ITS environment and relevant to the work developed in this dissertation. The architecture, standards, messages and protocols discussed in the first section are referent to the work developed in the European Union by the different bodies involved. The second section explores the characteristics of the two main access technologies used, a brief technological evolution, and how do they fit into the ITS environment. The chapter ends with a review of the current literature with work that contributed to the field of ITS.

2.1 Cooperative Intelligent Transport Systems

2.1.1 Framework

Information sharing and communication capabilities rise, in any system, its ability to become more flexible, reliable, and robust. Systems with these characteristics are becoming common in our society, thanks to the evolution of computers and their miniaturization, network performance, and processing capabilities. The state of transportation is already populated with several stand-alone technologies - electronic tolling, traffic information systems, variable message signs, personal vehicles with navigation and notification systems, infrastructure to track and manage traffic – confirming that intelligent systems are gaining widespread acceptance within the transportation community and by the general public.

C-ITS fits in the line of these information sharing systems, bringing information and communication technologies to the transportation infrastructures and vehicles in order to create more benefits in terms of transport security, efficiency and sustainability [10]. The benefits of C-ITS products must be clear to consumers to remove uncertainty, their costs must be justified against a wide array of competing automotive and consumer electronic products available on the market. Furthermore, it is also important taking into account a few policies to successfully implement a cooperative large-scale system [11]:

- Liability: Assuring citizens of product safety and the possibility to claim compensation in case of damages caused by defective products.
- Security: Cooperative systems will exchange information that might be relevant for (automated) decisions in which the safety of human lives depends. Therefore, it is mandatory to ensure no malign intervention can threaten the health of road users and other traffic participants.
- Privacy: Cooperative systems will imply the creation, storage and exchange of personal data over wireless communications links. There is a massive amount a data involved, that could be considered as personal data, as they can lead to tracking the movements of individuals. It is important to guarantee anonymity in data exchange.

A system that shares critical information should be carefully planned and managed. On the other hand, if all stand-alone technologies presented in today's road networks were able to communicate, and every single one of them have the capacity to share information with all agents involving it's environment, all the benefits mentioned before could be accomplished and substantially enhanced. The communications involving these types of information sharing (ITSC) should be exclusive to the transportation environment, performed by dedicated devices, and be able to deliver real time ITS services to road users throughout Vehicle-to-Vehicle (V2V), Vehicle-to-Infrastructure (V2I) or Vehicle-to-Vulnerable Road User (V2R), or even Infrastructure-to-Infrastructure (I2I) communications. Thus, currently, ITS development is moving towards cooperative solutions and making use of short-range communication technologies such as ITS-G5 and long-range communication technologies such as LTE (cellular) to achieve interactions such as the aforementioned ones.

2.1.2 Architecture

ITS Station

According to ETSI terminology, an ITS-S is a functional entity specified by the ITS-S reference architecture [12], referring as a set of functionalities rather than a physical unit. Based on the Open Systems Interconnection (OSI) model, this reference architecture is extended in order to include specific features, access technologies and protocols to handle ITS services (figure 2.1). The ITS-S reference architecture is composed by four horizontal layers, in which three can be directly mapped in the OSI model, and are flanked by two vertical entities [12] [13][14][15]:

Access layer: Represents the layer 1 and 2 of the OSI model - namely physical layer and data link layer – that supports the various protocols, interfaces and types of media responsible for external and internal communications. For external type communications some of the technologies could be non-ITS specific, (UMTS, LTE, 5G) or some ITS exclusive (ITS-G5).

Network and Transport layer: Represents the layer 3 and 4 of the OSI model – namely network layer and transport layer – that comprises the networking protocols (e.g. IPv6, GeoNetworking), the addressing and routing data from source to destination, (being them between ITS-Ss or between ITS-S and other network nodes) and geographical-based data dissemination. The transport protocols provide end-to-end reliable data exchange and additional features such as flow control and congestion avoidance, depending on the various types of requirements imposed by other layers.

The dynamic selection of ITS access technologies, the handover between them, the number of subsystem components (vehicles, personal devices), auto-configuration, multiple interface management as well as interoperability between IPv6 and IPv4, makes the usage of IPv6 within the layer essential.

Facilities layer: Represents the layer 5,6 and 7 of the OSI model – namely session layer, presentation layer and application layer – and the main purpose is to assist the ITS applications that require shared data and offering access to common functionalities. To achieve this, three groups of facilities are defined:

- Application support facilities provides common functions to assist the ITS Basic Set of Applications (BSA) and management of the ITS-S lifecycle. This includes discover, download and maintain services as software modules, without resulting in an unstable system that jeopardize the driver experience. Some functionalities include: CPM management, DENM management as well as Human Machine Interface (HMI) support, to name a few.
- Information support facilities aims to standardize, store, aggregate and maintain data from various sources of information (received by the communication channels and from the sensing capabilities of the vehicle itself). The main entity present in this facility is the Local Dynamic Map (LDM), that based on the functionalities aforementioned, is able to build a data model of the local environment.
- Communication support facilities in cooperation with the Networking and Transport layer holds the dissemination strategies (broadcast, geocast, unicast) necessary by the ITS BSA, as well as initialize, close and maintain communication sessions.

Applications: Provides ITS service through ITS applications, relying on common functionalities and data provided by the facilities layer. ITS applications are authorized, prioritized, maintained and classified in the context of ITSC.

Management: Responsible for cross layer functionalities between different layers, transmission and synchronization management, security and privacy functions management as well as the configuration of the ITS-S itself. It also grants access to the Management Information Base (MIB), an entity which is responsible to define important data variables and data sets.

Security: Provides different security and privacy functionalities that are responsible for performing security operations and storing credentials used by security protocols and mechanisms used in the different horizontal layers. Such functionalities include key management, hardware security, firewalls, encryption or decryption, and identity authentication.

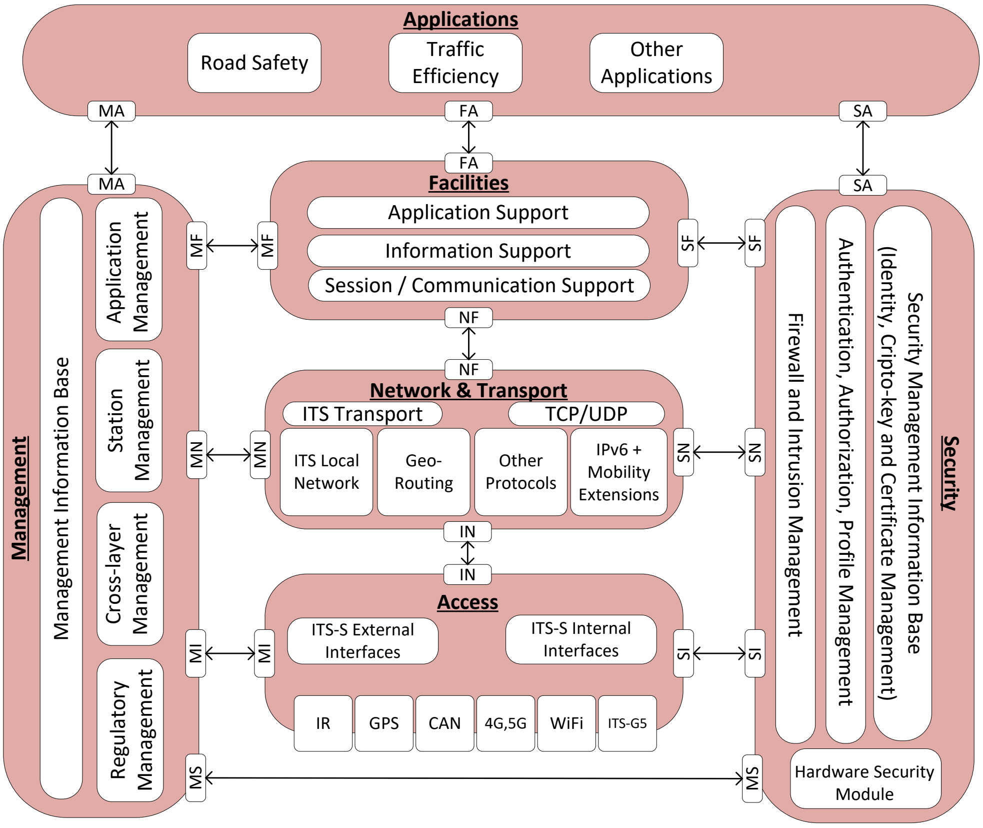

Figure 2.1: ITS-S detailed architecture with possible elements (adapted from [12])

ITS-S functional components

An ITS-S should be comprised by several functional components, and each one of these components could be specified based on their functionalities and which layers of the ITS-S reference architecture they used. According to ETSI [12], an ITS-S can be composed of four functional components:

- **ITS Station Host**: Provides access and functionalities to the ITS applications.
- **ITS Station Gateway**: Has the main function of connecting two different OSI protocol stacks at layers 5 to 7, and the capability of converting protocols through the facilities layer. It provides connection between the ITS-S internal network (that connects the different ITS-S components) and the external proprietary networks.
- **ITS Station Router**: Interconnects two different ITS protocol stacks at layer 3, excluding the Facilities Layer and the Applications Layer in their functionalities. They provide connection to other ITS-Ss and are capable of converting protocols.
- **ITS Station Border Router**: It provides the same functionality as the ITS-S router with the difference that is able to connect an ITS-S protocol stack to a non-ITS network protocol stack that may not support the security and management principles.

ITS Sub-systems and stations

Depending on which of these functional components is deployed, an ITS-S is meant to be part and work in the context of larger ITS entities namely ITS Sub-systems, that in addition to the ITS-S it comprises other control and communication systems. These communicating entities act like a single node in the overall ITS and can be divided into four types (figure 2.2) [12]:

- **Personal Sub-system**: Provides access to ITS applications through a portable user device. It comprises a personal ITS-S that includes a ITS-S Host.
- **Vehicle Sub-system**: Hosts ITS applications that can collect information about the vehicle, and its environment through the ITS-S gateway. This sub-system could be mentioned as an On-Board Unit (OBU). It comprises a vehicle ITS-S that includes a ITS-S gateway, a ITS-S host and a ITS-S router.
- **Roadside Sub-system**: Hosts ITS applications and it is an equipment installed along the roadside infrastructure (hence, it is commonly mentioned as RSU). It could be connected to the proprietary roadside network through the ITS-S gateway to access data collected by roadside sensors, or even connect components of the roadside system (e.g. variable message signs, traffic lights) to the ITS-S internal network. It comprises a roadside ITS-S that includes a ITS-S gateway, a ITS-S host, a ITS-S router and a ITS-S border router.
- **Central Sub-system**: Management, monitorization and support functionalities to the ITS applications regulated by different agents. This entity acts as a service provider. It comprises central ITS-S that includes a ITS-S gateway, a ITS-S host and a ITS-S border router.

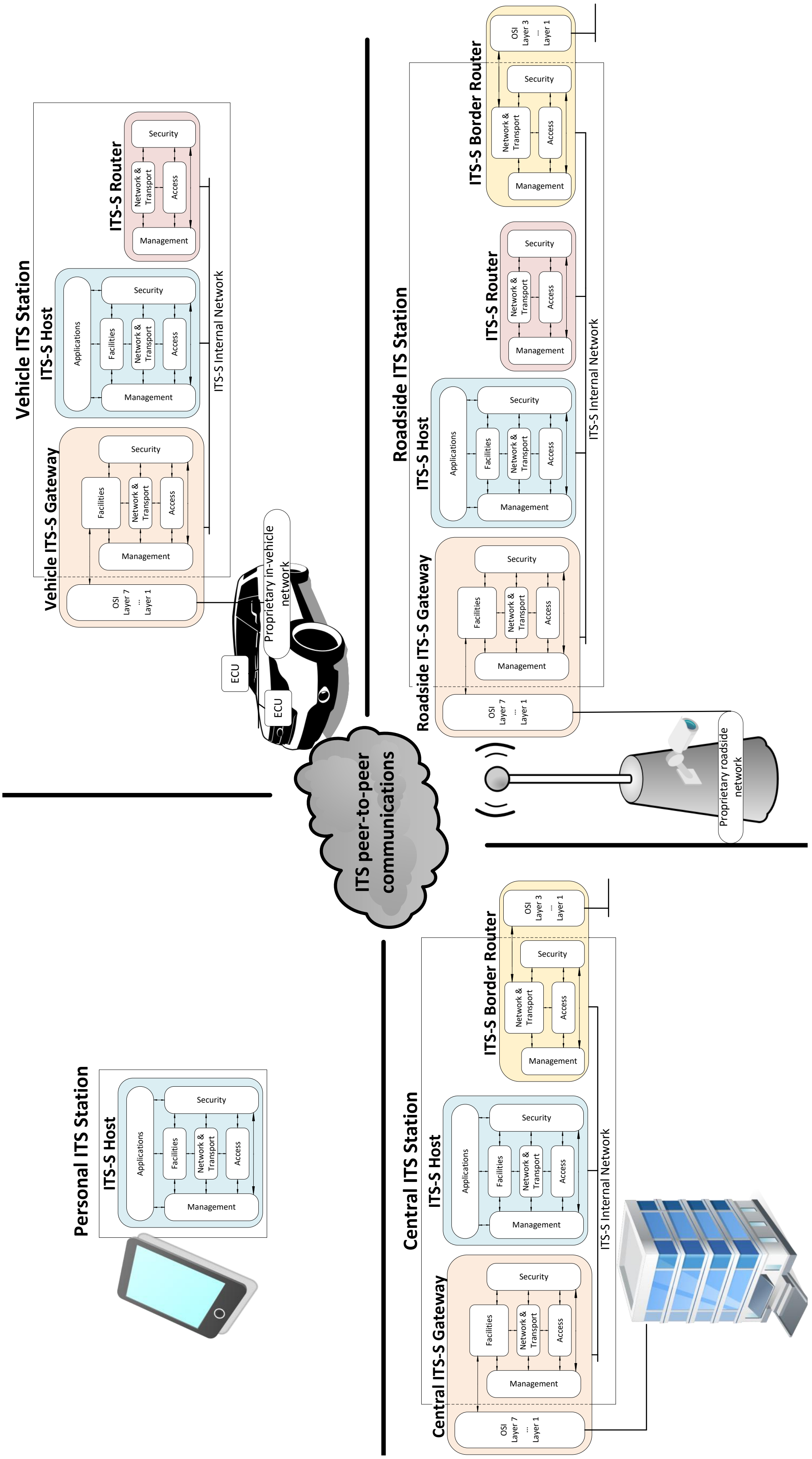

Figure 2.2: ITS Sub-systems (adapted from [12])

ITSC Networks

Being the central element of the ITS architecture, the ITS-S relies on communication networks to successfully implement cooperative services. These networks could be classified into internal networks and external networks, being the first ones responsible to interconnect ITS-S functional components (e.g., ITS-S Host to ITS-S Gateway), while the second ones are responsible of interconnecting ITS-Ss among each other (e.g. vehicle ITS-S to roadside ITS-S) or connect ITS-S to other network entities (e.g., Internet Server).

There are several external network types in ITS and they are grouped into ITS domain and Generic domain [12]. The ITS domain networks refer to the networks which are specified in ITS standards, while the Generic domain networks refer to other networks used for ITS and other purposes as well. A high level of abstraction for the external network types could be visualized in figure 2.3 and they can be described as follows [14]:

- **ITS ad hoc network**: Through dedicated wireless technologies (e.g., ITS-G5) this network enables direct short-range communications among personal ITS-Ss, vehicle ITS-Ss and roadside ITS-Ss. This type of network is categorized by its great flexibility and mobility, forming arbitrary network topologies without the need for a coordinating entity.
- **ITS access network**: Dedicated network that provides access to specific ITS services and applications, as well as connection between the roadside ITS-Ss. These types of networks are usually deployed by road operators, and can provide indirect connection between vehicles ITS-Ss (via roadside ITS-S, alternatively to the V2V communications), or even connect the roadside ITS-Ss to a central ITS-S (e.g., road traffic management center).
- **Public access network**: Provides access to general purpose networks that are publicly accessible. LTE network is an example that provides mobile internet access to a vehicle ITS-S.
- **Private access network**: Provides data services to an exclusive user group for a secured access to a private network such as a company's intranet.
- **Core network**: Grants legacy services to the ITS-S, such as World Wide Web (WWW) or email, through the public access network and the private access network.

In addition to these external networks where the ITS-S could act as a forwarder or source of data, it can also be attached to the proprietary legacy networks such as a Controller Area Network (CAN) in the case of a vehicle ITS-S sub-system or, a legacy roadside infrastructure in the case of a roadside ITS sub-system. The different networks shall provide support for at least one of the use cases of road safety, traffic efficiency, infotainment and business applications, however, it is presumed that the communication within a single network does not meet all the requirements of all applications and use cases, and thus, combinations of networks are envisioned in which multiple ITS access and networking technologies are applied [14].

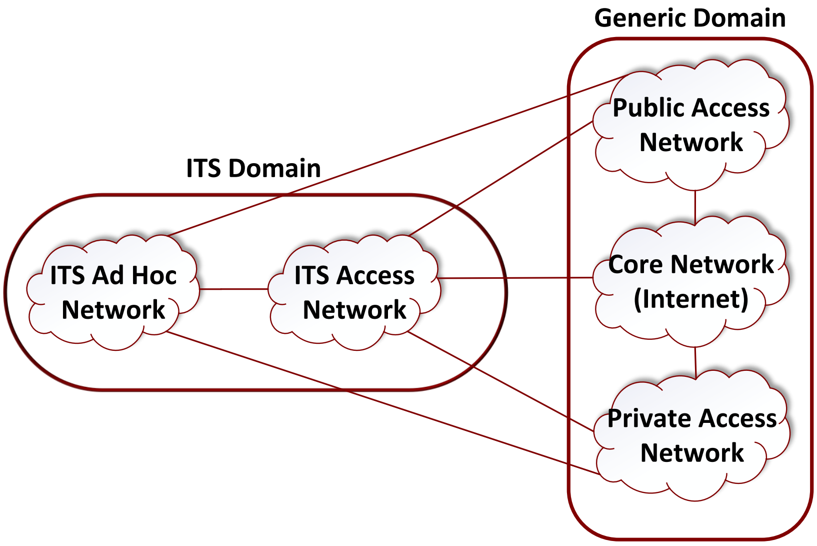

Figure 2.3: ITSC Networks (adapted from [14])

ITS Applications

Being the most superficial layer of the architecture, the ITS applications are in charge of providing ITS services to the users with the objective of covering all the use cases of the roadside environment. The ability of the ITS-S to gather, prioritizing and manage information from different sources, provides to the user reliable and live data compiled in a form of applications that should cooperate between them to achieve the best Quality of Service (QoS) possible. Each application comprises one or more use cases but not all of them, therefore, an entire set of possible deployable applications are defined by ETSI to cover all the three main ITS application classes and all the user needs and requirements. The BSA comprises [16][17][18]:

Road safety applications: These applications are the most critical and more resource demanding, therefore they should be prioritized and have the minimal latency values when compared to other applications. They are identified as the ones that are deployed to decrease the probability of traffic accidents and the loss of lives from the vehicle's occupants - or at least minimize the consequences - by providing data and improving the driver's awareness by sharing information between vehicles (by means of V2V communications) and roadside units (by means of Infrastructure-to-Vehicle (I2V) communications). Some examples of these applications are collision risk warnings, emergency electronic brake lights, hazardous location notification, or signal violation warning.

Traffic Efficiency Applications: They provide traffic information to the road users and are aimed to improve traffic flow and assistance. Traffic efficiency messages are usually disseminated to the vehicles and personal ITS-Ss through a roadside ITS-S, by broadcasting the messages to a specific area. The information could also be initiated by a central ITS-S which provides information related to an application of a roadside ITS-S, for being disseminated in a specific area. One group of these applications are speed management applications where they notify the speed limits or even provide information about the signal phase and timing of a traffic light for an optimal speed advisory. Another group are the cooperative navigation applications that aim to increase the traffic efficiency by managing the vehicles navigation through cooperation among OBUs and between OBUs and RSUs.

Infotainment Applications: Aimed to deliver on-demand information to the road users on either a commercial or non-commercial basis for entertainment and comfort services. These applications are the least priority and have a better delay tolerance as well as a higher data exchange rate. Furthermore, these applications can be sub-divided into co-operative local services where infotainment is obtained based on local services such as point of interest notification, media downloading, parking management or public transport management. The other sub-class is known as global internet services that offers community services which includes insurance and financial services, fleet management or ITS-S lifecycle that comprises software/data provisioning, updates, and calibration.

2.1.3 Messages

The ability for a road user to have at his disposal information about his surroundings beyond its sensorial range enhances its capacity to predict, calculate, and avoid critical safety situations. The traffic load that mainly flows by means of the ITS network is based on different types of messages generated by the different ITS-Ss present in the roadside environment, and each type of message has a specific contribution to respond to the corresponding use cases present in all applications defined in the BSA. Each one of these types of messages are generated by the corresponding service present in the ITS-S that also assures the maximum reliability and security possible for the dissemination and operation of the messages in the network. The messages elements need to be defined and respect different requirements to achieve standardization and the best performance possible of all the ITS system.

Cooperative Awareness Messages

Cooperative Awareness (CA) within road environment plays a major role for several road safety and traffic efficiency applications. The information is exchanged within the ITS network (comprises V2V, V2I, V2R communications) and is packed into Cooperative Awareness Messages (CAMs) that contains basic status and attributes of the originating ITS-S, (e.g., for vehicle ITS-S: position, motion state, dimensions) allowing the receiver to evaluate the messages relevance and real-time information, and act accordingly to different situations. The construction, encoding, management and processing of CAMs are performed by the CA basic service, which is an entity comprised of the application support facilities in the facilities layer.

This entity interfaces with the ITS applications layer and the LDM (present in the facilities layer) to forward the received CAM content for further processing. To get the necessary information the CA basic service interacts with the data provisioning facilities, that are responsible of providing data for CAM generation within the facilities layer. For transmission and reception of CAMs the CA basic service interfaces with the Network and Transport layer using the services provided by GeoNetworking/Basic Transport Protocol (BTP) or the IPv6/GeoNetworking stack protocols. At the sender ITS-S, the CAM is passed to this layer embedded in a Facility-layer Service Data Unit together with Protocol Control Information (PCI) according to the BTP [19]. At the receiver ITS-S, the CAM shall be passed from the Network and Transport layer to the CA basic service. It may also exchange information with the Management entity and the Security entity regarding some elements of the CAM Packet Data Unit (PDU). The general structure of the CAM PDU could be visualized in figure 2.4 and it's composed by [20]:

ITS PDU header: Includes the information of the protocol version, the message type and the originating ITS-S ID.

Basic container: Includes basic information regarding the originating ITS-S (e.g., type of originating ITS-S, latest geographic position of the ITS-S).

High frequency container: Includes highly dynamic information of the originating ITS-S (e.g., speed, position)

Low frequency container: Includes a more static data of the originating ITS-S (e.g., vehicle dimensions, sensor status)

Special vehicle container: Includes specific information about a vehicle role of the originating vehicle ITS-S (e.g., towing truck, dangerous load transportation).

Each of these containers are composed by Data Elements (DE) and Data Frames (DF) and although having several containers, the CAM PDU length can vary according to the originating ITS-S, for example it could not be necessary for a station include a special vehicle container in its CAM PDU or even some specific DE in its containers [20]. Considering several environmental conditions, the application requirements and the channel usage requirements of the Decentralized Congestion Control (DCC) (present in the ITS-G5), the CAM generation rate is comprised between **1Hz** and **10Hz** for a OBU, and a maximum of **1Hz** for a RSU.

The other factor that should be taken into account is the generation time of the CAM, that refers to the difference between the time at which CAM generation is triggered and the time that the CAM is delivered to the networking and transport layers for dissemination. This time should not exceed **50 ms** and for a coherent interpretation of the receiving ITS-S each CAM shall be time-stamped. Although having a big slice in the ITS network's load, since they are constantly being disseminated into the network without a specific trigger event, the CAM is transmitted only from the originating ITS-S in a single hop to the receiving ITS-Ss located in the direct communication range of the originating ITS-S, ergo a received CAM shall not be forwarded to other ITS-Ss [20].

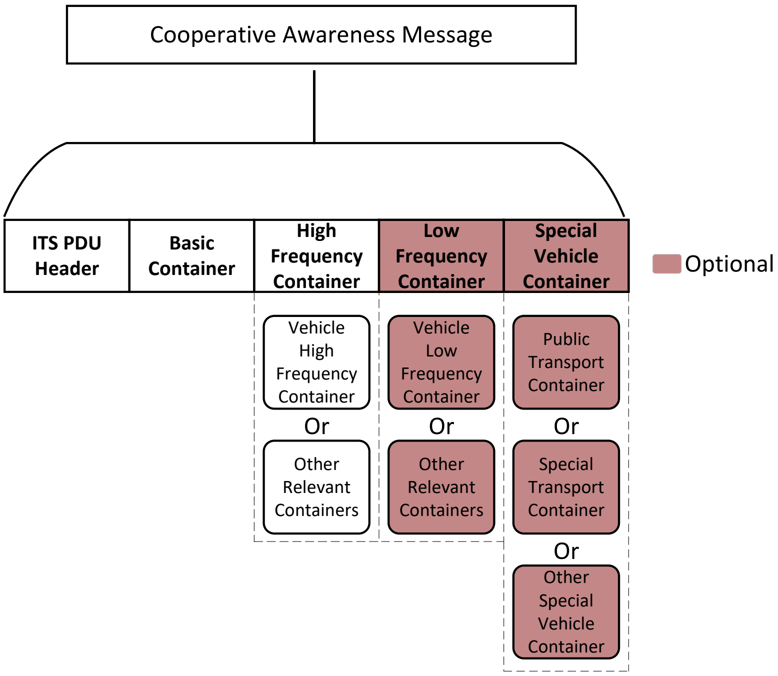

Figure 2.4: Cooperative awareness message structure

Decentralized Environmental Notification Messages

Comprising some of the use cases related to road safety and traffic efficiency, more precisely to the Road Hazard Warning (RHW) application, the Decentralized Environmental Notification (DEN) basic service, is an application support facility in the facilities layer that construct, encode, manage, forward and process Decentralized Environmental Notification Messages (DENMs). These messages are disseminated into the ITS network providing information related to a road hazard (e.g., type of hazard and position of the hazard) or abnormal traffic conditions to the driver. The DEN basic service interfaces with the ITS applications layer to receive the application request for DENM transmission or to provide the received DENM content directly to the application. Depending on the conditions, the application could request different types of DENMs, namely [21]:

- **New DENM**: Generated by the DEN basic service when an event is detected for the first time by an originating ITS-S, it is labelled with an identifier and provides some event characteristics such as event detection time, event position and event type, to name a few.
- **Update DENM**: Generated by the originating ITS-S, which previously had generated the New DENM for the same event, provides some updated information and an updated timestamp.
- **Cancellation DENM**: Informs the ending of an event, and it's transmitted by the originating ITS-S that generated the new DENM for the same specific event.
- **Negation DENM**: Used to announce the termination of an event that has been previously disseminated by other ITS-S.

For transmission and reception of DENMs, the DEN basic service interfaces with the Network and Transport layer. For transmission purposes the DEN basic service provides the PCI to this layer and rely on services provided by the GeoNetworking/BTP stack (e.g., geographic area dissemination) or by the IPv6/GeoNetworking stack. At reception if an ITS-S is entitled as the destination of the DENM, the message shall be passed from the Network and Transport layer to the DEN basic service. The DEN basic service also interfaces with the Management entity and Security entity for information exchange. The general structure of the DENM PDU could be visualized in figure 2.5 and it's composed by [21]:

ITS PDU header: Includes the information of the protocol version, the message type and the originating ITS-S ID.

Management container: Includes information regarding DENM management and DENM protocol.

Situation container: Includes information that describes the event detected.

Location container: Includes information of the event location, relevance area, and the location referencing.

The à la carte container: Includes additional information that could be needed for transmission and it is not present in the other containers.

The last three containers shall be optional, thus, depending on the type of DENM that is being transmitted the length of the message could vary, in addition, each container is composed by a sequence of DE and DF that can also be optional or mandatory depending on the situation.

As mentioned before, the generation of new DENMs implies the association with a unique identifier that is a combination of a ITS-S ID and a sequence number. The time interval regarding DENM transmission repetition is not defined, although the ITS application responsible for the DENM generation event should provide a repetition interval parameter and a repetition duration parameter. The DENM repetition should be applied to the most updated DENM regarding specific identifier, and if no repetition parameters are not provided, the DENM repetition will not be executed. Another important concept is the relevance area, that is set by the ITS application of the originating ITS-S, with the objective of defining the area that the event could have a direct or indirect impact. Contrarily to the CAM dissemination, the DENM could be forwarded by different stations in order to get to as many ITS-Ss as possible within the relevance area [21][22].

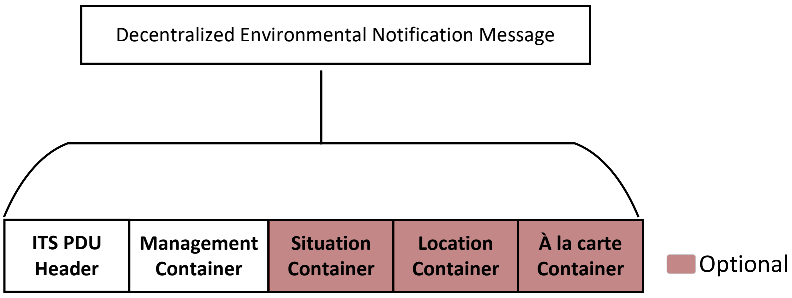

Figure 2.5: Decentralized environmental notification message structure

Infrastructure Messages

The fixed nature of the RSUs and their strategic positioning can elevate their impact on conflicting situations and potentially dangerous areas, such as intersections and traffic light segments. Although sensorization helps understand the surroundings of an ITS-S, additional information can be provided to complement this data and improve traffic fluidity or even avoid collision situations, especially in these areas. Since the road topology does not change very often, messages could be disseminated providing traffic light status, intersection topologies, and even the movement status of other vehicles at a given time. With this information the receiving ITS-Ss can estimate the potential risk of certain maneuvers or pedestrian behaviour and act accordingly.

The infrastructure services, located at the facilities layer, aim to provide various types of information regarding the road elements and topologies. Each instantiation provides its own message with different requirements and parameters to several applications [23] [24]:

- **Traffic Light Maneuver (TLM) service**: It aims to provide safety-related information to help vehicles or pedestrians execute safe maneuvers in a intersection area. The TLM service provides real-time information about the operational states of the traffic light controller, that is, the current signal state and the time left to the next state changing. It provides detailed green way advisory information to perform allowed maneuvers and safe crossing, as well as public transport prioritization. This way, movement in these conflicting areas can be done in a controlled way. This information is disseminated through Signal Phase And Timing Extended Messages (SPATEMs) that are triggered by the application that provides all the content to the TLM service.
- **Road and Lane Topology (RLT) service**: It provides the digital topological map of a certain infrastructure area. This description includes the lane topology for vehicles, bicycles parking, paths for pedestrian crossings and the allowed maneuvers in the corresponding area, complementing the information already present in the SPATEM. The service disseminates Map Extended Messages (MAPEMs) in which the data is fed up by an application. The same MAPEM is disseminated until the application indicates to transmit a new content MAPEM or to terminate the

dissemination process.

- **Infrastructure to Vehicle Information (IVI) service**: It is intended to provide information regarding road signs, being them static, variable, physical, virtual or temporary road work. This information is disseminated through the Infrastructure to Vehicle Information Messages (IVIMs) with a corresponding identification number in order for the ITS-S to differentiate the organization/service provider that transmitted the message. The messages can be classified by:
  - New IVIM: If an application triggers the dissemination of the messages.
  - Update IVIM: If the service provider intend to update the information of a certain IVIM, or to add the end time to it.
  - Cancelation IVIM: If the service provider that initiated the IVIM dissemination intend to terminate it.
  - Negation IVIM: If other service provider (i.e., the one that do not initiated the IVIM dissemination) intends to terminate it.
- **Traffic Light Control (TLC) service**: It supports prioritization to public transport or public safety vehicles like police, fire brigade or ambulance to pass through intersections or a defined route as fast as possible. This is achieved by vehicles that disseminate Signal Request Extended Messages (SREMs) to the infrastructure ITS-S to request traffic light signal priority/advantage. After sending the request to the traffic control center for operation, the infrastructure will respond to the SREM request with a Signal request Status Extended Message (SSEM) indicating if the request has been granted, cancelled or changed to a more relevant SREM request (e.g., an ambulance takes precedence over a public transport). Each SREM or sequence of it, have a unique identification number that is used by the SSEM as well to respond to the correct request.
- **GNSS positioning correction (GPC) service**: It is intended to deliver positioning correction data for Global Navigation Satellite System (GNSS). This position correction is provided by the Radio Technical Commission For Maritime Services Extended Messages (RTCMEMs) that supports various types of positioning systems (e.g, RTK, Global Positioning System (GPS), GLONASS), and are generated by the RSU. This information is continuously transmitted for the surrounding moving ITS-Ss, providing more helping data for the execution of location based maneuvers.

Collective Perception Messages

Rather than disseminate the station's current state, i.e position or velocity, the ITS-S can also share information regarding several agents that had been detected by their local sensorial system. The Collective Perception (CP) aims to exchange the locally perceived objects (e.g. obstacles, vulnerable users, legacy vehicles) in the network, reducing the uncertainty in the road environment for the ITS-Ss by contributing with information to their mutual Field-of-Views. With CAM aggregation information, this concept enhances and enables safety applications based on received information about objects located outside the range of an ITS-S's perception sensors (e.g., warning of oncoming traffic in a intersection without Line of Sight (LOS)) [25]. The CPS is the entity located at the facilities layer responsible to generate, receive and process CPMs, which contains information concerning the detected objects, as well as information status regarding the originating ITS-S and its sensory capabilities.

Instead of sharing traffic regulation information, the CPM needs to comprise objects located near the driving lane or in adjacent lanes that could potentially compromise road safety. An object should be associated with a certain confidence level that is computed by a sensor fusion system, usually proprietary. The confidence level needs to be unanimous within the transmitting ITS-Ss, therefore confidence metrics need to be harmonized in the road environment to avoid ambiguity upon reception. This parameter is also applicable at the free space measurements, i.e, the path between the sensor making the measurement and the object detected.

It is expected that different ITS-Ss detect the same object leading to redundant and worthless updates broadcasts, and therefore increasing the network load unnecessarily resulting in CPM losses and the performance degradation of the CPS. Several mitigation rules could be applied, reducing the message length by omitting some perceived objects that fit pre-defined redundancy mitigation rules. Although maintaining a balanced network load is important, it only make sense to apply these mitigation rules when the load surpasses a certain threshold, otherwise the CPM needs to include all the perceived objects to ensure maximum reliability within the road environment. The CPM format is illustrated in figure 2.6 and it is described as follows [26][27]:

ITS PDU header: Includes the information of the protocol version, the message type and the originating ITS-S ID.

Management Container: Includes information with respect to the originating ITS-S type and the reference position that is used to identify objects relative to a global reference point (e.g., in the case of vehicle ITS-S the reference point is the ground position on the center of the front side of the vehicle).

Station Data Container: Includes more detailed information that complements with the data provided by the Management Container regarding the originating ITS-S. In the case that the originating ITS-S is a vehicle, the attributes will be listed in the Originating Vehicle Container that comprises the dynamics of the vehicle (e.g. vehicle speed, acceleration, orientation angle, roll angle, pitch angle) in order to shape objects described in the Perceived Object Container (present in the same CPM) into a target reference frame. Some of this information is already transmitted by the CAM, although, because of the delay between the reception of the two messages, an additional computation would be necessary to estimate the dynamics of the originating vehicle on the receiving vehicle side, that could result in inaccuracy. This container also supports trailer description if the detected object is detected by sensors that are mounted in the trailer. In the case that the originating ITS-S is an RSU, the attributes will be present in the Originating RSU Container, which provides references to match data provided by the CPM with the representation of an intersection or road segment that is provided by map messages disseminated by the RSU.

Sensor Information Container: Includes information regarding the sensory capabilities (e.g., perception range, area of perception) and the type of perception system (e.g., Radio Detection and Ranging (RADAR), Light Detection And Ranging (LiDAR)) of the originating ITS-S, that are later used by receiving ITS-Ss to derive the areas that are currently sensed by nearby vehicles. Each described sensor is identified by an ID.

Perceived Object Container: Includes information of every object that has been perceived by an ITS-S, this is data describing the dynamic state and the properties of the detected object. The object is described in relation to the reference point in accordance with the Management Container, it is identified by a unique ID and associated with the ID of the corresponding sensor that performed the measurement. A timestamp of the measurement is also included as well as the distance, speed, angle dimensions, and acceleration of the object in a three-dimension plane.

Free Space Addendum Container: Includes information to classify within different confidence levels the detection area of a particular sensor. This container should be included whenever a sensor cannot use its entire detection area to reliably provide a free space indication, i.e, different confidence levels could be mapped into the sensor's detection area to derive different classes of reliable information (e.g., when the sensor measures two vehicles driving behind each other, and they are detected by a rear sensor, the information regarding the latter vehicle should have a less confidence level than the information regarding the first one).

The CPM generation frequency is managed according to the channel usage requirements provided by the DCC (for ITS-G5), nevertheless, the frequency should be truncated to either **1 Hz** or **10Hz** for both vehicle ITS-S and roadside ITS-S. Even if no objects were detected or do not meet the requirements to be included in the message, the CPM should be transmitted anyway to report that is able to detect and share objects. In the extreme scenario where the CPM is dropped by the DCC in the access layer (for example, due to channel congestion), the objects presented in the dropped CPM could be included in CPM segments as soon as possible [27] [28].

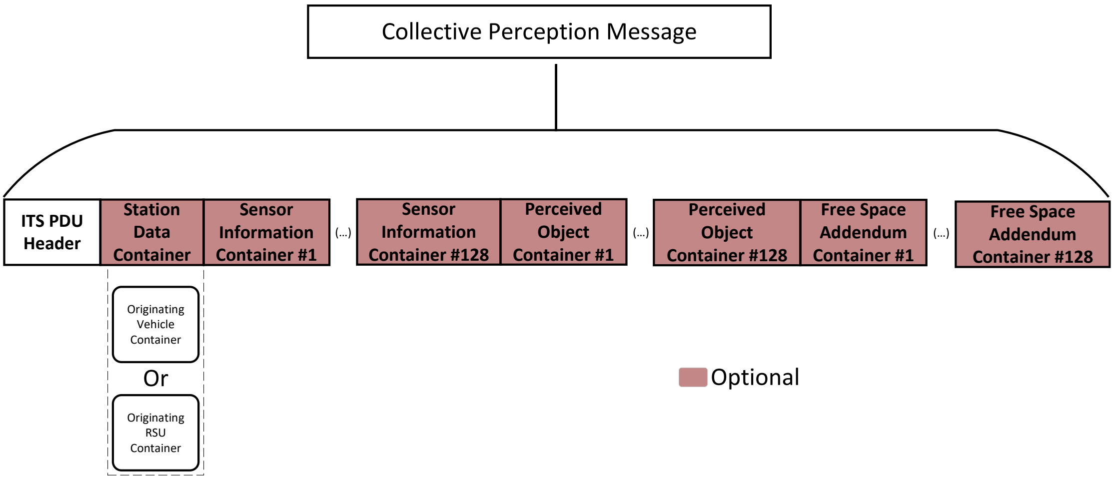

Figure 2.6: Collective perception message structure

Maneuver Coordination Messages

Automated driving systems are becoming more common in vehicles present in the road environment, aiming to provide a more comfortable and safest driving experience to the driver. Currently, these systems are only capable of reacting to maneuvers that are already being performed. If the vehicles have the ability to share information which contains their planned trajectory, the driving capabilities of Automated Vehicles (AV) could be fairly enhanced since it has information of the intended routes and maneuvers of the neighboring vehicles.

Aiming to reduce prediction errors from the automated driving systems, exchange information about intended maneuvers between vehicles, and specify the interaction protocol (to perform joint maneuvers if conflicts happen), the Maneuver Coordination Service (MCS) is currently in the standardization process by ETSI [29][30]. Similar to other services presented, the MCS will be located in the facilities layer with the purpose of serving specific applications in the above layer. Specific applications could mean to serve specific scenarios where coordination is imperative such as lane merge, platooning, lane overtaking, lane change or intersections [29][30][31][32][33]. Besides the specific scenarios the MCS needs to address a more generic approach where Maneuver Coordination Messages (MCMs) are exchanged regardless the scenario that the vehicle is currently facing or will face. To achieve this, [34] and [35] imply three phases for coordination:

- **Detection phase**: Every vehicle broadcasts MCMs which contains its planned trajectory, that is a spatial-temporal description of the vehicle's movement. Since a vehicle has the future movement off all the neighboring vehicles, if the two planned trajectories happen to intersect (occupy the same space at the same time) the vehicle without the right-of-way priority (less priority) need to change is trajectory in order to avoid collision.
- **Negotiation phase**: After a conflict has been identified, the low priority vehicle

broadcasts a new trajectory denominated desired trajectory. This will be interpreted by the receiving vehicles as a need for coordination if the desired trajectory will intersect with their own planned trajectory. The receiving vehicle, according to its own parameters, will evaluate if it is willing to change its planned trajectory to adapt to the request. If the receiving vehicle accepts the request, he updates its planned trajectory. If the request is not accepted the low priority vehicle withdraws its desired trajectory and stays with its planned trajectory (this could mean the low priority vehicle need to stop to avoid collision).

- **Execution phase**: If the receiving vehicle accepts the request, both desired trajectories will result in planned trajectories and both vehicles perform the joint maneuver. In case of unforeseen events during the execution phase the receiving vehicle could abort the maneuver.

The protocol defined by the MCS is based on right-of-way rules which in theory surpasses safety over fairness. The receiving vehicle is always the one who decides if it is willing to forego its right-of-way for the sake of enabling the lowest priority vehicle maneuver, that in some cases could provide traffic flow or improve a vehicle's driving situation (e.g., in a traffic jam the vehicle with the right-of-way gives a gap so that a vehicle coming from a lane merge could enter the main lane). In this situation, a vehicle with the right-of-way could submit a cooperation offer for the lowest vehicle priority considered in its requested maneuver [32].

Considering the CAM approach, [36] proposes a MCM format (figure 2.7) that includes several parameters that brings some needed redundancy when allied with the messages already discussed. The format supports messages provided by vehicles or by RSUs:

ITS PDU header: Includes the information of the protocol version, the message type and the originating ITS-S ID.

Generation Delta Time: Includes the timestamp of the generation time of the MCM.

Basic container: Includes basic information regarding the originating ITS-S (e.g., type of originating ITS-S, latest geographic position of the ITS-S). This container is the same as the basic container from CAM messages, although this rejects the fact that the maneuver process needs to rely on CAM exchange.

Vehicle Maneuver Container: Includes the planned trajectory and desired trajectory of the vehicle, as well as certain dynamics such as heading, speed, acceleration, among others. The container also includes a field where it's possible to respond to an RSU notification regarding an advice to help vehicles in the maneuver. The notification is identified by an ID and the vehicle can accept or discard the advice by filling a data element reserved for the effect.

RSU Suggested Maneuver Container: Includes different data elements that holds various types of information regarding the road environment that the RSU is inserted into. This can include lane ID, road segment ID, intersection reference ID, among others. This information is intended to provide vehicles with speed, geographical location, and timing advices to perform the best joint maneuver possible. The advices provided by the RSU are targeted for a specific vehicle and therefore are unique.

The insertion of RSUs in the maneuver process could substantially enhance the performance of the service in complex traffic situations by providing coordination and suggestions for better vehicle decisions (e.g., speed advice), improving fairness and perception. Although it is intended to be inserted in a connected environment, the MCS is being developed to include legacy vehicles within the use cases in which the RSU and the CPS can provide another layer of reliability and awareness.

The MCM generation frequency needs to be dynamic depending on scenario in question. A more static environment like a highway jam traffic should have a less generation frequency since the maneuver can be performed in a slower time pace. On the other hand, a more dynamic environment could require more updated information in a smaller time window (similar to CAM and CPM) [36].

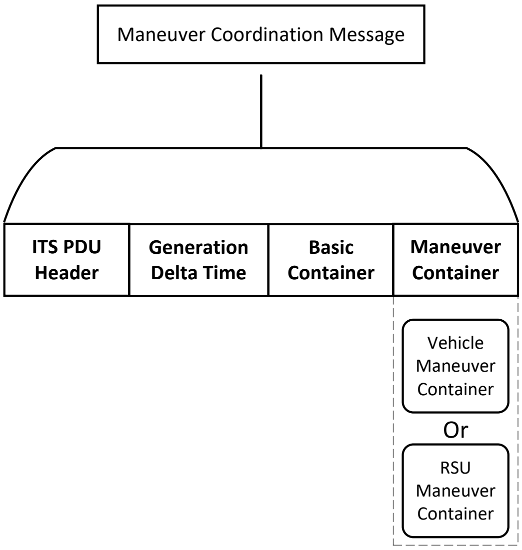

Figure 2.7: Maneuver Coordination message structure

2.2 Radio Access Technologies

Several wireless technologies have been proposed to meet the Cooperative, Connected and Autonomous Mobility (CCAM) communications requirements under different vehicular networks scenarios. Some technologies aim for close-range communications requirements, such as, low latency and dynamic topologies that usually handles a big slice of the messages previously mentioned, while others, aim for long-range communications that carries bigger amounts of data and better-quality coverage. The former group usually supports communications within a Vehicular Ad hoc Network (VANET), that accommodate momentaneous networks in which the nodes (OBUs or/and RSUs) are able to exchange information without relying on a management infrastructure. These types of networks usually handle the most priority data for safety applications and therefore need to overcome challenges such as scalability [37], connectivity disruption, network overload [38], and even security issues [39]. In Europe, the European Conference of Postal and Telecommunications Administrations (CEPT) determined that the 5.9Ghz radio frequency spectrum was suitable for vehicular communications purposes [40], and in compliance with this study, ETSI advanced with the standardization of radio equipment operating in this band [41], resulting on the EU Commission Decision in allocate the radio spectrum in the 5.875Ghz to 5.905Ghz frequency band [42] for ITS applications usage. The spectrum is divided into 4 sub-bands that comprises several service channels and one control channel, all 10 MHz wide [43] (figure 2.8). The sub-band ITS-G5A is dedicated to road safety related services, while ITS-G5B comprises the non-safety road traffic services [44]. The ITS-G5C is used to provide means of operation in the Radio Local Area Network (RLAN) [45] and the latter, namely ITS-G5D, is reserved for future use of ITS services.

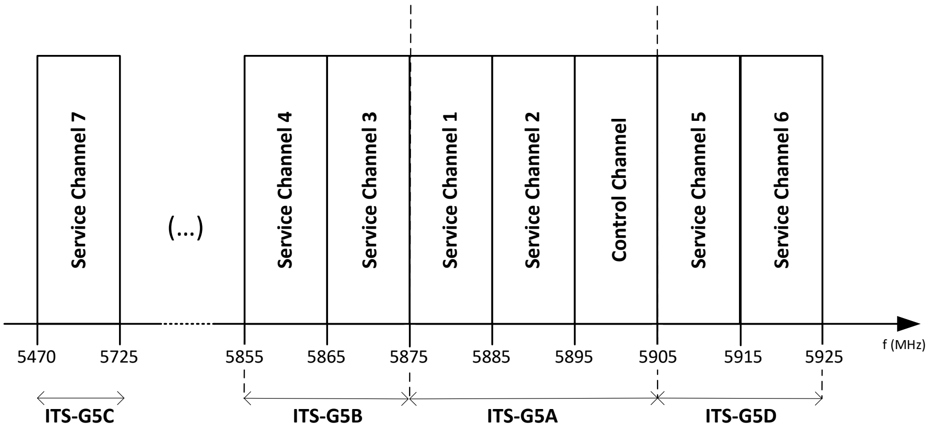

Figure 2.8: Spectrum allocation for ITS applications (adapted from [46])

The combination of the two types of communication technologies (short-range and long-range) and the ability for the ITS-S to choose from multiple Radio Access Technologies (RAT), creates an hybrid approach and enables cooperative services with various communication and QoS requirements, as well as resilience to various types of connectivity conditions. While

Vehicle-to-Everything (V2X) communications comprises maneuver coordination and collision avoidance applications that requires low latency communications and smaller amount of data, Vehicle-to-Network (V2N) communications aim for quick information dissemination over large areas, which usually involves bigger quantities of data [47].

2.2.1 ITS-G5 Radio technology

As stated in the ITS-S architecture section the access layer hosts the two lowest layers of the protocol stack known as the data link layer and physical layer, where the former is subdivided into (figure 2.9) [46]: a) the Logical Link Control (LLC), which provides the capability of distinguish between different network layer protocols through the SubNetwork Access Protocol (SNAP); b) the Medium Access Control (MAC) that is responsible for scheduling transmissions to prevent interference among ITS-Ss; while the physical layer is fully compliant with the IEEE 802.11-2016 [48]. To cope with some of VANET's challenges a distributed management cross-layer entity known as DCC [49], regulates the network traffic load throughout several techniques like Transmission Power Control (TPC), Transmission Rate Control (TRC), and Transmission Datarate Control (TDC).

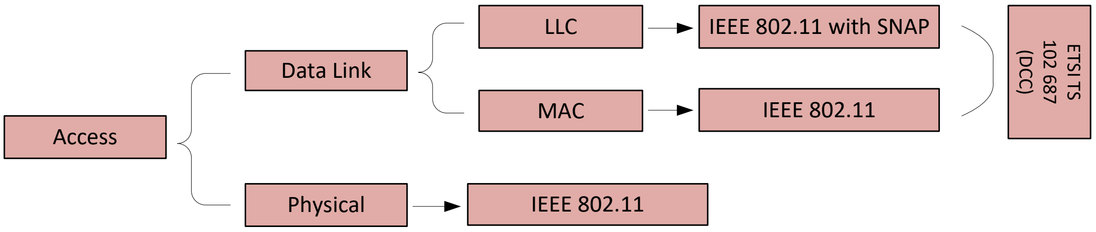

Figure 2.9: Access layer separation and respective protocols (adapted from [46])

Fitting in this layer, one of the wireless technologies specified for the ITS-S architecture is termed ITS-G5, a technology based on the IEEE 802.11p standard. The IEEE 802.11p-2010 [50] was firstly designed as an amendment to the IEEE 802.11-2007 [49] family of standards and carried to the IEEE 802.11-2016 [51] with the purpose of providing support to the vehicular environment. Theoretically, the standard supports velocities up to 200 km/h with a delay of 100 ms up to 1000 m of maximum range. It defines interfaces that allow communication with layers higher than the access layer, as well as describing the functions and services so that nodes can operate within a very dynamic environment and exchange messages among them without the need to join a Basic Service Set (BSS) [52].

The BSS is the smallest building block of an IEEE 802.11 network, it consists in a group of stations that can communicate with each other independently (Independent BSS) or by means of an infrastructure (Infrastructural BSS), and, although the Independent BSS could be called of ad hoc, it still carries a magnitude of complexity and overhead that cannot meet the vehicular communications requirements. All the association, synchronization and authentication procedures are executed every time a station wants to join a BSS, resulting in a time-consuming process, where transactions between the nodes in the road environment could not be completely accomplished if the brief time window of connection is spent performing these procedures [53]. Communications Outside the Context of a BSS (OCB) are achieved by setting the Basic Service Set Identification (BSSID) (which is the name of a BSS at a MAC level) to a wildcard in every frame transmitted in an 802.11p communication. This means that the vehicular environment needs to have predetermined channels, and that the channel scanning process no longer applies in this scenario [46].

In IEEE 802.11p, changes have been made at the Physical Layer (PHY) and MAC Layer that, in turn, modify some features already implemented in previous amendments like IEEE 802.11a-1999 [54] and IEEE 802.11e-2005 [55]. In the PHY it uses Orthogonal Frequency Division Multiplexing (OFDM) with BSPK, QPSK, 16QAM and 64QAM modulation, that allied with different coding rates achieves several transfer rates. To achieve 10MHz frequency channel bandwidths the 802.11p deploys the half-clocked mode of OFDM, this way it is possible to address some problems regarding the vehicular environment such as interference due to multi-path propagation and the Doppler shift effect [56].

In the MAC layer the medium access algorithm deployed is named Enhanced Distributed Coordination Access (EDCA) which is based on the Carrier Sense Multiple Access with Collision Avoidance (CSMA/CA) algorithm principles but adding QoS. This means that priority data traffic will have a higher probability of being transmitted by shortening the node's listening period of the medium (arbitration interframe space) [46].

Since the development of IEEE 802.11p, newer techniques and IEEE 802.11 technologies (e.g., IEEE 802.11ac , IEEE 802.11ax) have been deployed to cope with some of the previous standards limitations. These improvements can be leveraged into the vehicular environment, raising the reliability, troughput, and range for a better overall performance. With this in mind, a new technology is under development by the IEEE 802.11bd Task Group with the name of IEEE 802.11bd. With this new technology, a redefinition at the PHY and MAC layers level of IEEE 802.11p is achieved to assure support for bigger relative velocities (up to 500 km/h), twice the communication range, and tolerance for twice the MAC's throughput. Although being a step forward, the IEEE 802.11bd is intended to assure coexistence, interoperability, and backward compatibility with IEEE 802.11p since it already has a mature and well-established position within the ITS environment [57].

2.2.2 Cellular Communications

As referenced in the ITSC Network section, access to different networks cannot be performed by one standalone close-range radio technology. In order to achieve constant wireless access to the various types of networks and their correspondent services, ITS-Ss need to accommodate the means to support cellular radio technologies. Cellular networks provide connectivity among broad areas as well as data exchange rates that fulfill the generic services requirements. In the case of vehicular environment, such objectives could be achieved by means of the Fourth Generation Mobile System (4G) or by the Fifth Generation Mobile System (5G).

LTE is the fourth generation of mobile communication systems that was born from the necessity of competitiveness advantage from the Third Generation system (3G) also known as Universal Mobile Telecommunications System (UMTS) already deployed by the Third Generation Partnership Project (3GPP), an international group of telecommunications standards development organizations that aims to provide study reports and specifications to define cellular telecommunication technologies.

The success of UMTS and the exponential growth in mobile services, allied to the big amount of data traffic exchange as well as high-capacity content, resulted in the necessity of a new technology deployment. To overcome such challenges, it was firstly introduced the High Speed Packet Access (HSPA), an overall upgrade to the packet data performance of the UMTS system [58]. Although much higher data rates and lower delays were achieved by HSPA, improvements were under discussion in order to reach greater specifications and longevity for 3G systems, leading to the launch of studies for a long-term evolution of the radio access technology, that later on, resulted in the Release 7 Technical Reports 3GPP TR 25.912 [59], and 3GPP TR 25.913 [60] addressing the requirements and the design framework for the Evolved Universal Terrestrial Radio Access (E-UTRA) and Evolved Universal Terrestrial Radio Access Network (E-UTRAN) (an evolution of UMTS Radio Access Network (RAN)) [61] .

By the time Release 7 was frozen in 2007, the project (known as the Evolved Packet System (EPS)) had gain real momentum, where two work items were being developed simultaneously, one focusing in designing a new core network architecture (Evolved Packet Core (EPC)) namely System Architecture Evolution (SAE), and other covering the air interface, radio access network as well as the User Equipment (UE), namely LTE [1]. In December 2008, Release 8 was frozen and all the specifications for a mature LTE system implementation were stable and ready to be deployed [62]. Besides the low latency and high data rates requirements, other important improvements and new features like improved coverage, high mobility support, spectrum efficiency and interoperability among other networks were introduced, highlighting the incremental step that LTE took upon its predecessors. Table 2.1 resumes some of the more interesting specifications enhanced between the releases.

Specification	**Unit**	**UMTS (Rel.99-4)**	**HSPA+ (Rel.7-10)**	**LTE (Rel.8-9)**
Downlink Peak Rate	Mbps	0.384	42.2	100
Uplink Peak Rate	Mbps	0.128	11	50
User Plane Latency	ms	100	25	5
Cell Spectrum efficiency	bps/Hz	0.53	1.28	1.5
Carrier Bandwidths	Mhz	5	5	1.4,3,5,10,15,20
Connect Setup time	ms	1000	100	100

Table 2.1: Performance values of different cellular technologies

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[1] the name LTE was later adopted to refer to the whole project, and will be adopted in the rest of the document when referring to the EPS

Both the access network and core network have different approaches from the previous technologies, providing a less complex architecture by introducing more advanced elements with increased capabilities (figure 2.10) [62] [63] [64]:

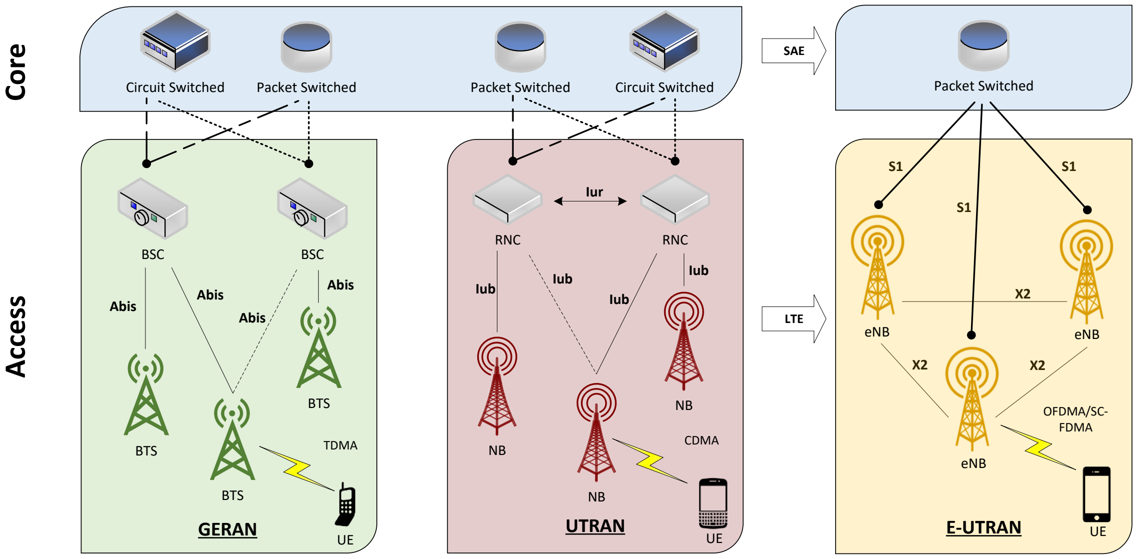

Figure 2.10: Different mobile systems architectures

- The Access Network is mainly formed by base stations named Evolved Node B (eNB), that just like the name suggests is an enhanced version of the UMTS Base Station Node B (that in turn replaces the Base Transceiver Station (BTS) from Global System for Mobile Communications (GSM)). Both Node B and BTS uses a centralized unit (Radio Network Controller (RNC) in UMTS and Base Station Controller (BSC) in GSM) that manages the radio resources and the handovers among the centralized units and the stations, as well as the connection to the core network. The eNB in E-UTRAN, eliminates the centralized unit by supporting all the radio resource control, admission control and mobility management that were previously contained by the RNC and BTS. Each eNB is connected to the core network by means of an S1 interface, and all the packet and signal forwarding are made throughout the X2 interface, that inter-connects the base stations. In terms of access technology GSM and UMTS used TDMA and CDMA respectively, which performs well for low data rate communications such as voice, but is very unstable over high-speed transmissions, therefore, OFDM is adopted in LTE, which in turn is more spectral efficient and bring high data rate support as well as solution for other problems such as multipath interference or narrowband interference.
- The Core Network suffered a transition from the alternating circuit-switched/packet-switched approach, to a fully packet switched approach, optimizing the data traffic delivery in LTE and all the costs associated with infrastructure. Nevertheless, this strategy requires different techniques to manage services that were previously handled

by the circuit-switched subnetwork in which voice was included. Since the packets are routed through the Internet Protocol (IP) such solution can be based on Voice over IP (VoIP). The architecture is split into the user plane and the control plane. The former is responsible for transportation of the user data traffic, while the latter handles management tasks (e.g., connection, mobility). Another improvement is giving the ability for the user to maintain an IP address whenever the device is switched on and released when switched off, something that do not happen in UMTS and GSM where an IP address was only set on request and disposed when was no longer required.

3GPP's Release 10 was the introduction to LTE-Advanced, that was conceived in sequence to the International Telecommunication Union (ITU) circular letter 5/LCCE/2 [65], triggering radio technologies proposals that could meet the requirements to be qualified as the International Mobile Telecommunications Advanced (IMT-Advanced) technology, also known as 4G. The enhancements for LTE were, at that time, already being documented under Release 8 Technical Reports 3GPP TR 36.912 [2] [66] and 3GPP TR 36.913 [67], meaning that LTE could fulfill some, but not all of every ITU requirements, and thus, to assure sufficient incremental steps between Release 8/9 and Release 10, 3GPP set a group of requirements for LTE-Advanced that in turn were more demanding that the ones previously established by ITU [68]. Besides the enhancements to the LTE system, Release 10 brought up some additional features such as, support to wider bandwidth through carrier aggregation, the use of advanced Multiple Input Multiple Output (MIMO) techniques and the introduction of relay nodes, improving the overall peak data rate, capacity, coverage and flexibility. In October 2010 LTE-Advanced was accepted as a 4G technology (along with WirelessMAN-Advanced) satisfying or exceeding all the requirements proposed [69].

The applicability of mobile technologies expanded beyond mobile broadband, the performance achieved by the subsequent improvement of features and the use of different techniques potentiated new services to be deployed in the mobile scene. One important feature relevant to the ITS environment was the introduction of Device to Device (D2D) communication as part of the Proximity Services in Release 12. Targeted for public-safety related communication services, this feature enables the data traffic exchange to be accomplished by means of a direct link (PC5 interface or sidelink) between two relatively close devices, discarding the necessity of using the Uu interface and the eNB for short-range communications and thus reducing latency values, resource usage and possible traffic injection into the core network [70]. Under the name LTE-Advanced Pro, subsequent releases led to enhancements to the technologies related to LTE and starting from Release 14, 3GPP started to address V2X communications by introducing the LTE-V2X, the first Cellular-V2X (C-V2X) set of standards aimed to provide support for vehicular communications. C-V2X operates at the same frequency as ITS-G5 and it is designed to support the same applications, raising interoperability and coexisting issues that eventually lead to the discussion about which technology should be deployed or how the spectrum should be shared [71] [72].

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[2] it was only approved in Release 9

The successor of LTE was already being discussed with studies that started in July 2016 by 3GPP regarding the search for a new 5G RAN later known as 5G New Radio (NR). The 5G requirements that led to focusing on several areas of 5G usage such as, enhanced Mobile Broadband (eMBB) or Ultra Reliable and Low Latency Communications (URLLC), were defined considering new services already implemented in the market and the necessities by different industry sectors (also known as verticals). The first 5G NR specification was part of the 3GPP Release 15, that introduced the Phase 1 of the 5G system deployment where two architectures were distinguished: the non-standalone version that relies on some of the elements in the LTE system, and the standalone version that is a fully 5G system architecture. Both architectures are visible in figure 2.11. In a non-standalone version only 4G services are supported but with different features provided by the 5G NR (e.g., lower latency), this was seen as a middle step and many current projects have been deployed in a non-standalone architecture. This version was highly motivated due to the little gap of frequency spectrum available in the current days for cellular networks, and market pressure to release 5G system parts as soon as possible [70]. Nonetheless, an enduring vision of the 5G system is to completely replace today's LTE infrastructure with 5G components both on the access network and core network [73] [74]:

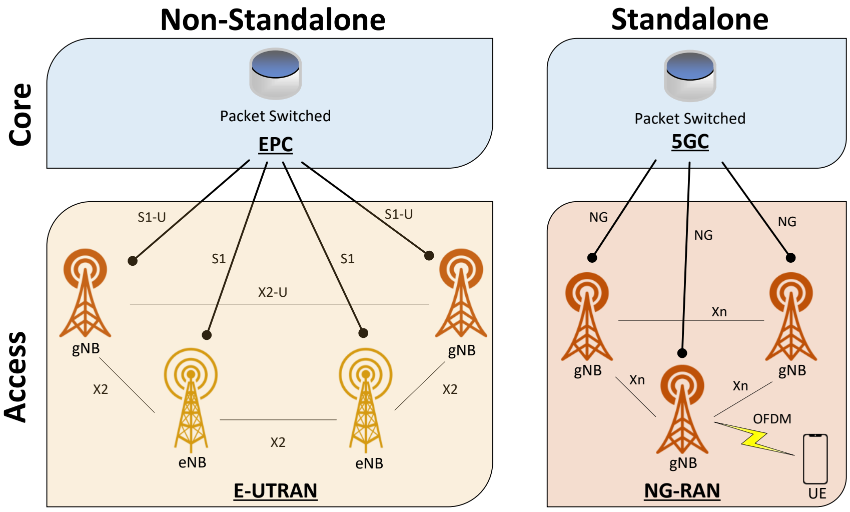

Figure 2.11: Comparison between the two 5G architectures

- The <u>Access Network</u> mainly formed by the (next) generation Node-B (gNB), a base station formed by several units that manages and controls several operations in the user and control plane. The gNBs are connected among each other by means of a Xn interface and to the core network through a NG interface. The connection to the UE is made by the NR interface, it uses a variation of OFDM namely OFDM with Cyclic Prefix (CP-OFDM) both in the downlink and uplink. However, an alternative can be used in the uplink plane referred as the OFDM with Discrete Fourier Transform precoding (DFT-s-OFDM), that provides low Peak-to-Average Power Ratio (PAPR) and could improve the uplink coverage.

- The Core Network is also split into the user plane and the control plane similar to the EPC. Although, the implementation of the 5G core elements is based on network functions that communicate with each other by sharing different services and resources. This creates a service-based approach architecture, that through virtualization enables modularity, reusability and new concepts such as network slicing and mobile edge computing [3].

Similar to the process taken for the IMT-Advanced proposal submission, Release 16 dictated the submission from 3GPP of a full 5G system for the IMT-2020 technology call that started back in 2016 by the circular letter 5/LCCE/59 [75]. This release represented Phase 2 of the 5G system deployment with features that complemented or enhanced Phase 1 technologies and techniques. In the matter of V2X features, the NR sidelink has been introduced giving the UE the ability to choose among the PC5 interface based on LTE, the PC5 interface based on NR, or even both, depending on the services that the UE is currently using, since the two technologies do not support interoperability [76]. Primarily stages of NR V2X already accommodate features of latest LTE-V2X releases, and with all the capabilities that the 5G system can provide, support to further applications such as platooning and remote driving can improve the overall experience.

5G system enhancements have already been defined in Release 17 with several areas of interest. Release 18 is yet to be defined, although some studies and specification work have already begun.

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[3] later known as Multi-Access Edge Computing

2.3 COLLECTIVE PERCEPTION SERVICE: A LITERATURE REVIEW

As transportation technologies converge into more automated and advanced systems, the cooperative benefits of ITS (C-ITS) start to become more evident, as it can improve the overall proprietary systems performance and reliability. Undeniably, the CA service provides fundamental information to the road environment that reduces uncertainties and overcome awareness challenges unachievable by vehicle drivers alone. On the other hand, the penetration of C-ITS technologies into real world implementation is going to be gradual, meaning that communication capable vehicles are, for a large period of time, to coexist with vehicles without these communication capabilities, and even before that, the local awareness of fully ITS enabled vehicles needs to be the best as possible to assure higher performance and resilience of the system. To do so, the CPS emerges as a viable solution to cope with these difficulties and to extend the information sharing nature of C-ITS.

In conjunction with V2V communications, the design of a good support infrastructure can leverage the performance of this service by providing viable information (through I2V/V2I communications) in more demanding situations thanks to the advantageous position, computation and communication capabilities of the RSUs. The review work of this section focus on examine some of the characteristics of the CPS, such as scalability and traffic load, and combine them with some of the features that a well placed RSUs could bring to potentiate the performance of the service.

With the C-ITS scaling, problems associated with communication channel load, obstruction and latency, start to become relevant and need to be addressed. Yicong Wang et al. [77] approach this scaling problem by quantifying the performance of the CP to different penetration rates of sensing vehicles in the road traffic with two metrics: sensing redundancy and coverage. Through analytical models and simulation it was showed that collaborative sensing is more reliable and robust (higher sensing redundancy) when a moderate vehicle density is achieved, while the coverage reliability is greater with higher density and penetration rates (even though a fairly high degree of reliability could be achieved with only a small percentage of sensing vehicles). Another factor was the relation between scalability of the CPS and the V2I traffic load, showing that from the initial penetration rate, the V2I resources are critical to safety-related applications. This traffic load (V2I traffic) will tend to diminish with the evolution of the CP penetration rate, but still maintaining great responsibility when is not possible to achieve V2V communication.

Gokulnath Thandavarayan et al. [78] also analysed the scalability factor of the CPS taking into account the CPM generation rules that serve as the measuring point between perception and channel load. Taking into account a CP penetration rate of 100%, the study considers two scenarios: low traffic scenario and high traffic scenario , where periodic CPM generation policies and dynamic generation policies are employed. In a first analysis it was showed that the dynamic CPM generation policies adapt significantly better to the traffic density variations since the objects detected are only included in the CPM based on certain motion rules, and thus, a less number of objects are included in the CPMs without losing object awareness (e.g, the lowest the object's speed, the less frequent the object is included in a CPM). This adaptation was also verified in the communication channel performance evaluation where the Channel Busy Ratio (CBR) and Packet Delivery Ratio (PDR) were measured. The CBR of the dynamic policies presented the lowest increase, while maintaining a good PDR from a low traffic density to a high traffic density scenario.

In addition to the CPM generation rules, [25], mentioned the fact that CPM transmitted in the control channel (figure 2.8), the same where CAMs are transmitted, could lead to channel congestion and degradation of both services, since CPMs are the most demanding in terms of message length and generation frequency. It was showed that at higher CP penetration rates, the CBR is similar for both cases when the CPMs are transmitted in a different channel and for the case when CPMs are transmitted in the same channel as CAMs, meaning that the DCC can drop a large amount of packets in the ITS-S in the last case. Nevertheless this packet drop results in a higher loss of object awareness and performance for both CA and CP services when operating in the same channel, showing that ideally, in high density scenarios both services should co-exist in different channels.

Better perception can indeed be achieved with more frequent transmission of CPMs even with a certain level of redundancy, however the implementation of certain rules for maintaining a balanced channel load are important for more demanding scenarios. G. Thandavarayan et al. [78] also denotes that a frequent transmission of CPMs that report information about a small number of detected objects will result in redundant headers that can increase the channel load and reduce the reliability of the CPS. This fact is discussed in [79], showing that the number of objects included in each CPM is lower than the effectively number of objects detected in both highway and urban scenarios. Gokulnath Thandavarayan et al. [79] purposes an algorithm, that is an improvement the ETSI CPM generation rules. The algorithm assumes a constant acceleration of the object and predicts if any of the objects detected that are not included in a current CPM generation event and would be included in the following CPM, should in fact be included the current CPM, avoiding the CPM generation with less number of perceived objects.

To tackle the problem of redundant headers, Ameni Chtourou et al. [80] explored the integration of strategic placed RSUs to avoid excessive CPM generation from OBUs in high traffic scenarios and take more advantage of new emerging technologies like for example mobile edge computing [81] [82]. In a first instance, by an analytical approach, the authors showed that CPMs generated by RSUs tend to include more perceived vehicles at different traffic densities, than the CPMs generated by OBUs. Allied to this, the I2V communications presents a higher PDR compared to a scenario where V2X (both I2V and V2V) communications are employed. Although limited to the RSU coverage area, these analytical results were then confirmed in Veins simulations, concluding that I2V communications can reduce the channel load while maintaining collective perception.

In the light of the French national project PAC-V2X [83], Pierre Merdrignac et al. [84] presented a cooperative system with the objective to augment the autonomous vehicle perception in critical safety zones by fusing information from their own perception system with the information received from CPMs and CAMs. This provides a level of redundancy and reliability to the cooperative system if the RSU is equipped with different sensors from the ones present in the communicating vehicles. In a first case it was evaluated how GNSS noise can impact the ability of a autonomous vehicle to localize surrounding vehicles by means of receiving CAMs or by local perception. The received CAMs show less resilience to GNSS noise, since it relies on this data to localize the transmitting vehicle, on the other the hand the local perception provides more accurate results even in high levels of noise. In a second case an RSU placement is evaluated in order to monitoring a certain region of interest, detecting all the vehicles at her range. As expected, the local awareness grown exponentially as the RSU transmitted more CPMs, without loss of precision even with the introduction of GNSS noise.

Beyond simulations, that supports the importance of RSUs in a collective perception environment, some real scenario projects have also been implementing infrastructure and evaluating the potential outcomes it could have in a automated road environment. Abhishek Jandial et al. [85] address the insights and the metrics to take into account by develop an roadside infrastructure composed by roadside sensors, a central perception unit, for CPM coding format, and a RSU for dissemination to assist AVs in specific areas. The requirements regarding location such as physical roadside conditions (e.g., building placement, site topology), object type detection (e.g., pedestrians, vehicles or both) and region of interest (e.g., search for blind spots) are evaluated to assure that the information provided by the infrastructure could be valuable as possible and not provide redundant data already captured by the local perception system of the AV. Another metric taken into account were sensor qualification. To have greater performance, sensors have different constraints and requirements such as their installation height, position and angle. The results of the implementation ended up showing that all requirements surrounding the infrastructure implementation alter the performance of the system. Significant variations in distance accuracy measurements and message transmission range were observed, meaning that, if a careful evaluation of the infrastructure components and the site isn't made, the RSU could end up providing ambiguous information degrading the whole collaborative perception concept.

Mao Shan et al. [86] conducted several experiments where a connected and automated vehicle relies only on the perception information provided by an RSU, equipped with several cameras and a LiDAR sensor. The AV also have cameras and LiDAR that are used for localisation to complement the GNSS for a better accuracy. Besides the demonstrations, it is addressed several uncertainty problems associated with the information transmitted in the CPMs. One aspect is the fact that each sensor measurement are corrupted with noise that could compromise the real positioning of the detected object in the field of view. This uncertainty could be mitigated with the use of different sensors that feed unique information into a sensor fusion system. Other aspect is the self-localisation from the transmitting ITS-S, where even stationary like RSUs are not completely free of localisation error. Different mechanisms that can localise the stationary or moving ITS-S could complement each other in order to provide the best accuracy possible. Nevertheless these uncertainties have to be taken into account. The first experiment, conducted in a real urban traffic environment, was a proof of concept of the CPS, where the connected vehicle could identify pedestrian crossing at an intersection without visibility, only by receiving CPMs from the RSU installed at the intersection. The second experiment, conducted in the CARLA simulator [87], is intended to demonstrate how a connected and autonomous vehicle reacts to pedestrians crossing the road, also relying exclusively on the information provided by the RSU, resulting in the vehicle successfully detect the pedestrian and perform a maneuver to avoid it. The last experiment, conducted at a controlled laboratory traffic site, demonstrated how the connected and autonomous vehicle predict a pedestrian behaviour based on the RSU information. The pedestrian moved towards a crosswalk in which the vehicle, without any available space to move through the road, stopped and waited for the road to be clear. These experiments highlight the importance of the CPS in road safety use cases, by improving the perception quality and reliability to the automated field. Besides V2V communications, the deployment of infrastructure poses as a great source of valuable information that brings robustness for decision making of drivers and autonomous operations.

Similar to the tests run in [86], EU research projects such as Managing Automated Vehicles Enhances Network (MAVEN) [88], Intelligent Maneuver Automation (IMAGinE) [89] and Transition Areas for Infrastructure-Assisted Driving (TransAID) [90] explores the CPS in real traffic environments. These projects enhance the importance of the CPS in the AV performance, more specifically in the infrastructure assisting information. TransAID focus on traffic management procedures and protocols so non-connecting vehicles and AV can coexist in the road environment, and how could the CP impact some use cases such as lane merging and hazard situations. Special attention is given to transition areas, that are special areas where AVs need to change their automation level to assure safety in different situations. Trials [91] showed that the infrastructure, due to the advantageous positioning, provide information to AVs that resulted in less transitions of control (handover of the vehicles control to the automation system to the driver or vice versa) and less risky maneuvers that smoothed their interactions and consequently the traffic flow. MAVEN's work focus on three intersection use cases (speed and lane change advisory, urban platooning, inclusion of non-cooperative vehicles and road users) in which the vehicles, using V2X communications, interact with the infrastructure and get the best possible advisory information for local perception, lane positioning and maneuver coordination. Besides the use of CAMs, SPATEMs, MAPEMs and the proposal of a new Lane change Advice Message (LAM), the use of CPMs help the AV to identify Vulnerable Road Users (VRUs) and legacy vehicles in intersections. Allied to CP, IMAGinE explores the integration of the MCS into some use cases like overtaking, highway speed and steering control, intersection turning, and strategic traffic distribution on the road.

Alejandro Correa et al. [36] also highlighted the infrastructure importance in maneuver coordination due to their neutral position in the negotiation process, their enhanced perception and ability to facilitate the coordination of multiple vehicles. If such automated coordination could not be achieved, the infrastructure could improve the transition of control experience by early inform vehicles and thus improve overall traffic flow and smoothness.

The design of a good infrastructure support for the cooperative and automated road environment is essential to maintain the different service performance needed to assure road safety. The physical limitations of V2V communications in more demanding scenarios can be complemented with I2V communications to satisfy all the BSA requirements. With newer services emerging like MCS that are extremely dependable of the information provided by the CPS, grows the need for CP deployment. Moreover, the RSUs acts has a communication point between the road and the traffic management center, that helps monitor and maintain order in the road environment. In the light of the reviewed literature, the work developed in this dissertation focused on the information that RSUs can provide and their importance on the early stages of deployment of an C-ITS atmosphere.

CHAPTER 3

Proposed System Architecture

This chapter illustrates the architecture of the system implemented in this dissertation. It explains the elements of the ITS-S implemented and how it relates to other elements of the overall architecture.

3.1 ITS Station and infrastructure

The construction of different types of ITS-Ss faces several problems regarding complexity since each one of them needs a set of particularities and requirements that must be met in order to operate. Looking back at figure 2.2, the ITS-S Host is the only functional component present in all of the four subsystems that comprises all the layers of the architecture capable of delivering access to the ITS applications. It becomes a relevant element in the design of the ITS-Ss and in their applicability to the road environment.

The software implementation of this work will focus on the main ITS-Ss in the ITS environment (since these are the only elements that benefit from the CPS): the RSU and the OBU. Although the RSU and OBU follow similar functional approaches, both of the ITS-Ss can be distinguished by some services and applications. The architecture used to implement the CPS is interoperable and it is based on previous work developed in partnership with A-to-Be [92] for the deployment of C-ROADS project in Portugal [93] [94]. It is built on the OSI-like approach mentioned in the previous chapter, i.e, it follows the ETSI ITS-G5 protocol stack for vehicular communications [12], where both layer organization, interfaces and services are built upon rules and requirements set by the ETSI standards (figure 3.1). The different layers are associated with different running services that communicate between them using specific SDUs that carry out encoded data to be delivered, treated, or managed by adjacent layers, making it easier to implement protocols, sub-services, applications or access technologies. This level of modularity is achievable by the implementation of the Abstract Syntax Notation One (ASN.1) coding rules to build these SDUs.

ASN.1 is a formal notation used for describing data transmitted by protocols regardless the language, physical representation or application. The notation is amplified by specifying several algorithms, namely, encoding rules, that describe how message values should be encoded for transmission [95] [96]. For SDUs, the Octet Encoding Rule (OER) is used while for publishing on the Message Queuing Telemetry Transport (MQTT) broker and over the air transmission the Extensible Markup Language Encoding Rule (XER) and the Unaligned Packed Encoding Rule (UPER) are used. The exchange of these SDU messages is done using the ZeroMQ networking library that creates communication sockets between services assuring message delivering.

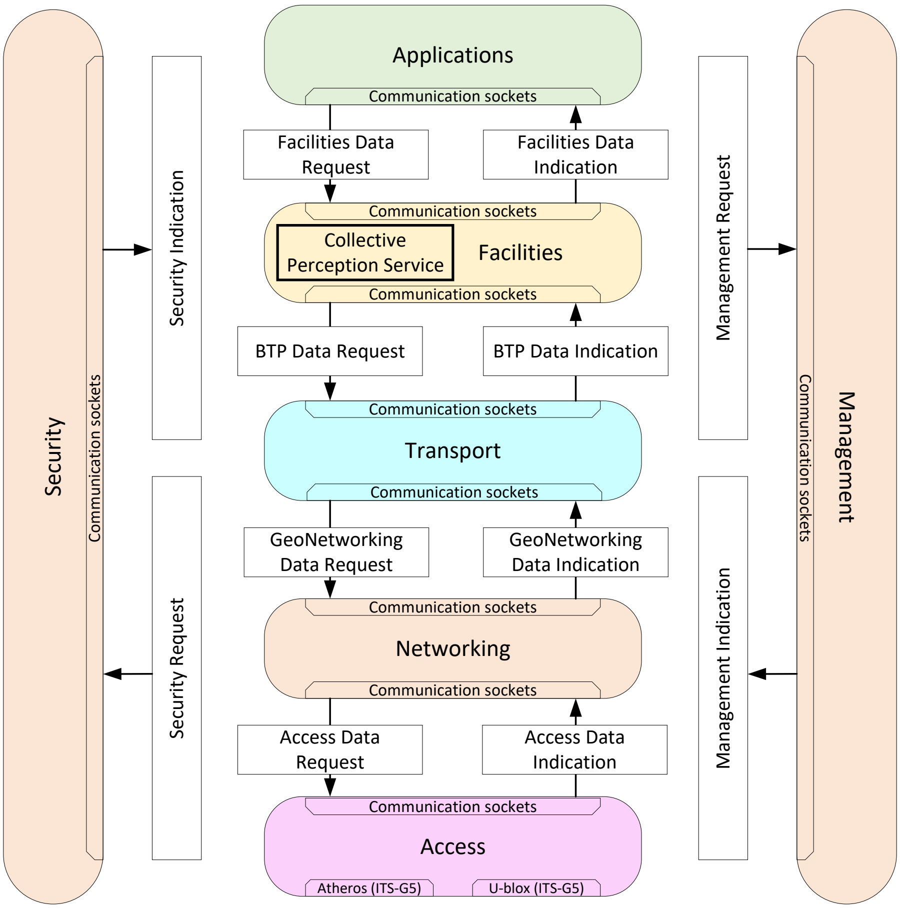


Figure 3.1: ITS-S architecture implementation and the corresponding SDUs

All sub-services are related to protocols, authentication procedures, encapsulation and decapsulation packets or even ITS basic services (present at the facilities layer such as the CA basic service):

- Access service manages the access technologies of the ITS-S and is responsible for decapping and encapping the Ethernet protocol headers such as the MAC and the LLC of the packets.
- Networking service mainly holds the GeoNetworking protocol header encapsulation and decapsulation.
- Transport service implements the BTP that provides the port numbers to address the upper layer services and is responsible for processing the BTP header.

- Facilities service holds various sub-services: the CA basic service, the DEN basic service, the IVI basic service and the CP basic service. All these sub-services, like mentioned in Chapter 2 , provide support for the corresponding messages that are consumed by the ITS applications.
- Security service aims to provide packet authenticity and trust management. It processes and verifies the secured header of the GeoNetworking packets and triggers local identity changes across layers for privacy purposes.
- Management service provides time and GPS coordinates for the requesting services. It manages the transmitting power in the access service to minimize harmful interference between ITS-Ss.
- Applications service is responsible for the interconnection with the C-ITS cloud platform by means of a MQTT broker for ITS message forwarding and system monitoring.

MQTT is a lightweight publish/subscribe protocol that is intended to provide an alternative to the client/server approach. Instead of communicating directly, the publisher and subscriber establish a connection between a middle-man called the MQTT broker, that filters the incoming messages and distributes them to the correct subscribers (figure 3.2). This is achieved by clients subscribing to specific topics of their interest that they can publish and/or subscribe without the need for topic configuration. In the case of the ITS framework these topics could be related to a geographic location or a specific ITS-S ID. The protocol also supports different QoS levels that define how reliable the connection between the broker and the clients must be, with the downside of higher latency and bandwidth values [97].

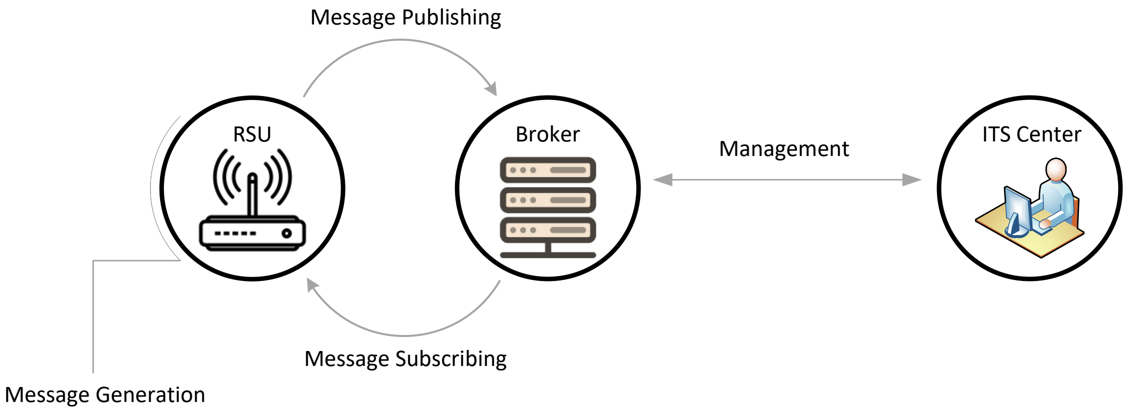


Figure 3.2: MQTT publish and subscribe schema

The only goal of the cloud platform is to hold the MQTT broker that serves as a communication bridge between, for example, an RSU and the central office. The RSU publishes the ITS messages it transmits, as well as the ones that it receives through ITS-G5 from other ITS-Ss. The MQTT broker was implemented as a service in a machine present at Instituto de Telecomunicações - Aveiro (IT), prior to this work. Using the publish/subscribe protocol allows the system to perform near real-time communication over all the elements, as well as simplify scalability whenever needed. The RSU also transmits a periodical heartbeat messages which includes summarized information about the current operating status such as CPU and memory usage, IP address and the number of active ITS events under coverage area. From the central office it is also possible to manually trigger event messages such as DENMs and IVIMs that can be disseminated by certain RSUs based on the geographic-based topic system implemented in the MQTT broker.

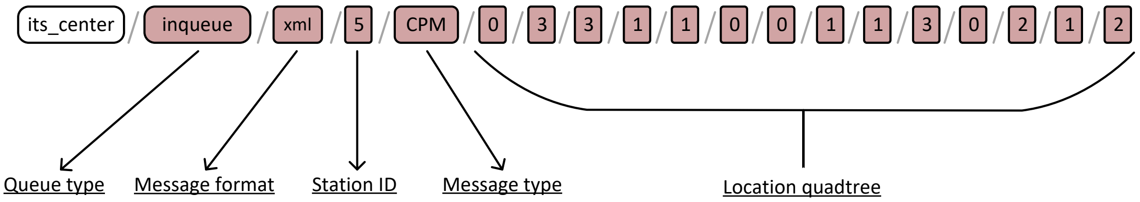


Figure 3.3: MQTT topic structure

Figure 3.3, represents an example of a possible hierarchical structure of a topic:

- ***Queue type*** indicates the message destination agent. It can acquire two values: inqueue for messages published by RSUs, or outqueue for messages published by the central office.
- ***Message format*** indicates the message encoding type that could be binary or XML.
- ***Station ID*** indicates the ITS-S identification number.
- ***Message type*** indicates the ITS messages types.
- ***Location quadtree*** indicates the geographical location of an RSU following a quad-tree map system representation.

The quadtree map system representation follows a tree data structure in which the children and parent nodes represent regions of the world map. The map is recursively subdivided into four quadrants, allowing different precision levels depending on the number of times the map has been divided (figure 3.4). This approach is also suitable for topic creation on the MQTT broker since the quadrants could be enumerated and a certain region could be specified by a sequence of numbers. Looking at the MQTT topic from figure 3.3, it is possible to see that the location-quadtree field of the RSU has a zoom level of 14 since the map is divided 14 times that corresponds to the amount of numbers present in the *Location quadtree* field, although if the central office wished to disseminate a message within a bigger dissemination area the zoom level could be reduced, as long as the RSU is subscribed to the outqueue topic of the central office.

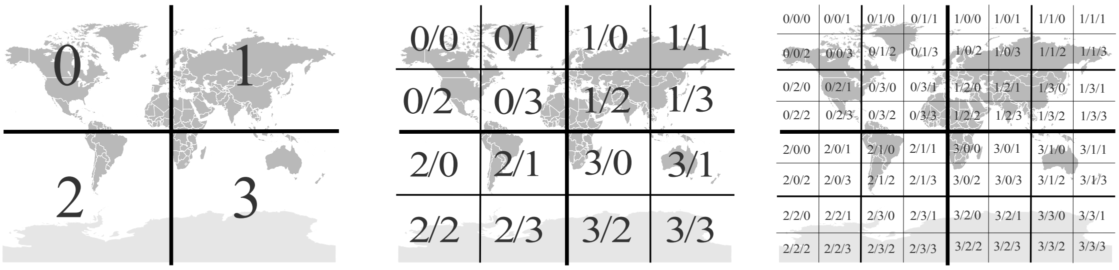


Figure 3.4: Quadtree map division

From the central office, the messages produced by the RSUs as well as their current status can be visualized in a web based dashboard. The dashboard interprets the messages from the cloud MQTT broker and allow for the traffic management operator to graphically visualize the dissemination location of the different messages. It also offers a way of generate road traffic events in a user-friendly manner, that will be disseminated in to area of interest through the outqueue topic of the MQTT broker. In addition, the dashboard (figure 3.5), by making use of the hearbeat messages, allows the visualization of the geographic location in the map of the system RSUs that are distributed along the highway A25, IT, Praia da Barra and Praia da Costa Nova.

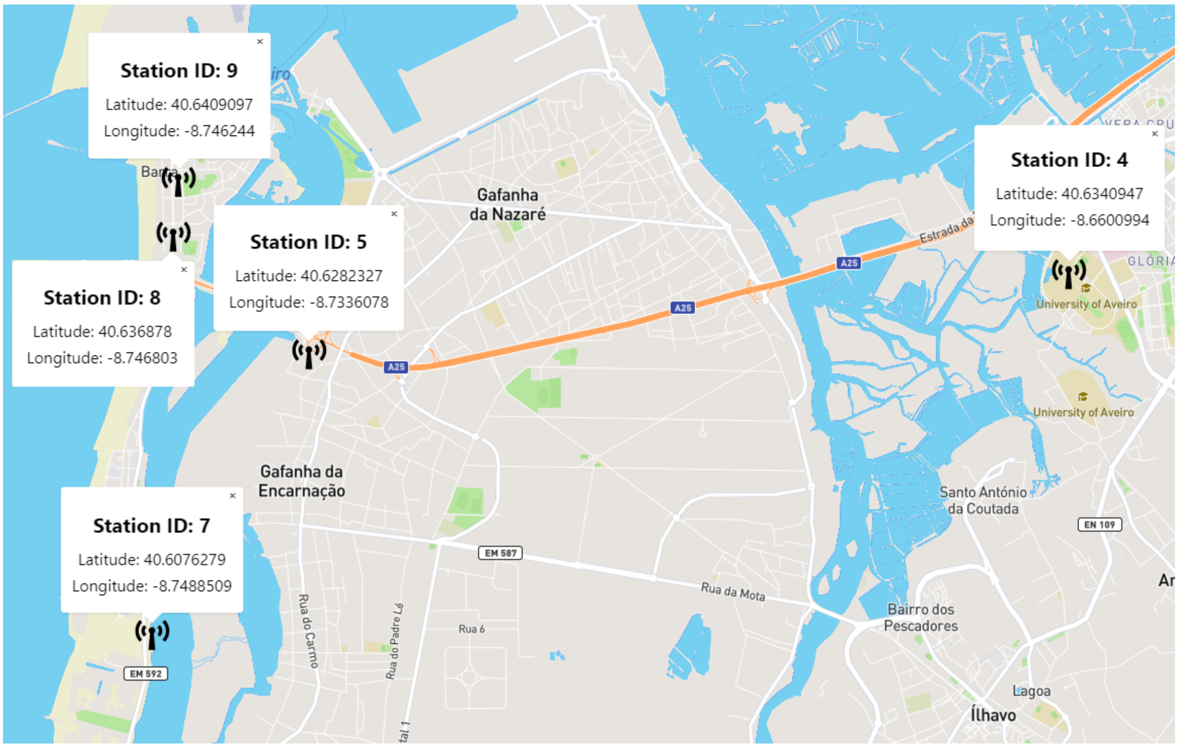
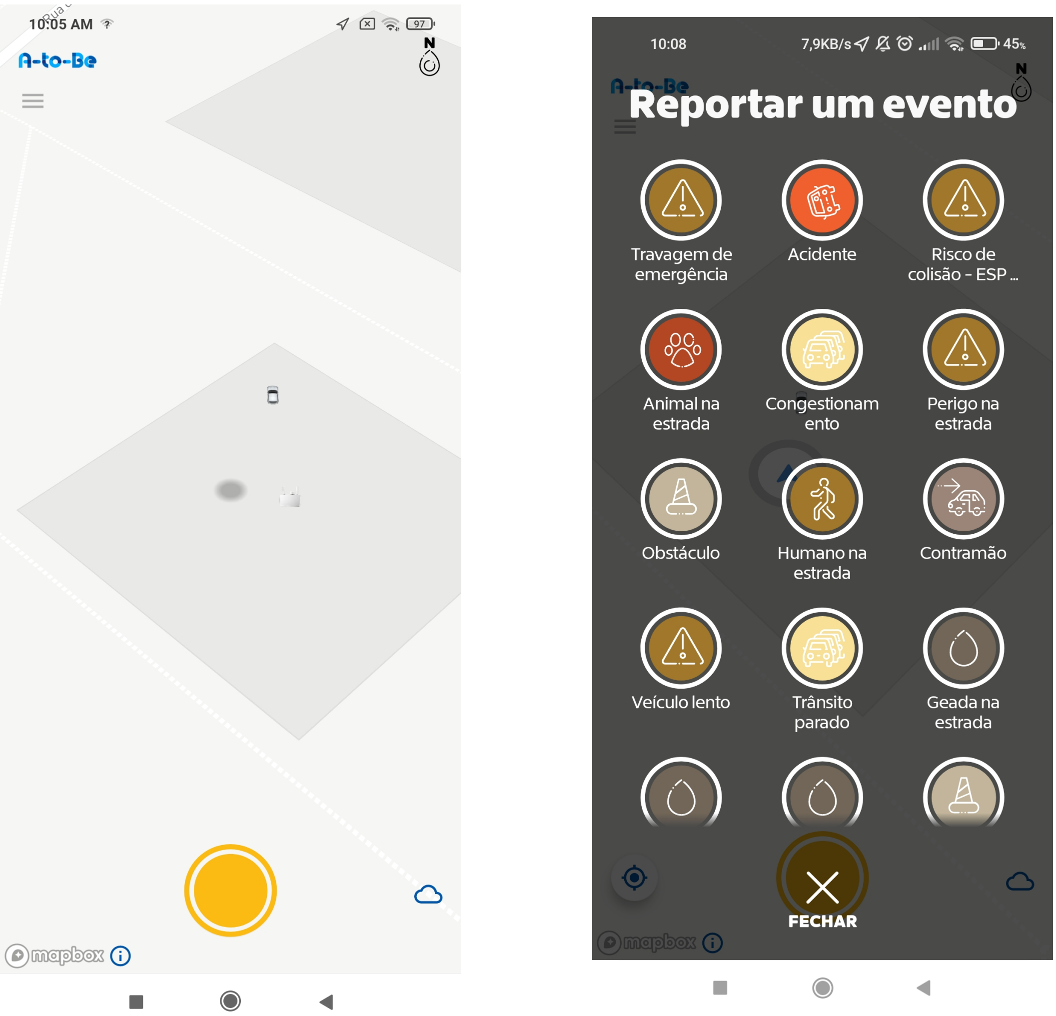


Figure 3.5: Map of all the RSUs

In the OBU perspective, the same architecture is used (figure 3.1) with a slightly different approach for ITS message generation. Connected to the OBU via wireless access point, there is a mobile application, developed in IT and later used for the C-ROADS project, that communicates with a local MQTT broker self-hosted by the OBU. The mobile application serves as a HMI, allowing the generation and visualization of events received by ITS-G5 or by the cloud MQTT broker, that the OBU receive and redirects to the local broker to be visualized in the mobile application. In figure 3.6a the mobile application is connected to an OBU that is sending CAMs through ITS-G5, that in turn are received by the RSU in which for a defined period of time also disseminates CAMs, being possible to visualize both in the mobile application. Figure 3.6b, shows the dissemination events that the application gives to the user. A DENM is then published in the local broker and disseminated through ITS-G5.



(a) Position of an OBU and RSU

(b) Possible events for dissemination

Figure 3.6: Mobile application demonstration

The overall system conceptualization is represented in figure 3.7 and, like it is mentioned in Chapter 4, depending on the installation location of the RSUs, in order to connect to the broker the RSUs have different physical connection types. In addition to this, all of the RSUs have a cellular connection that adds some redundancy in case of connection failure.

In this architecture both the web and mobile application where the information could be visualized were developed by the Embedded Systems group of IT, although this context helps visualize the importance of these elements in the development and integration of this dissertation's work in the overall system architecture. It is also worth mentioned at this point, that the IP camera does not contribute with any information to the CPM generation but is an important element to visually assure the synchronization and veracity of the data produced by the radar and that is later reflected in the messages published.

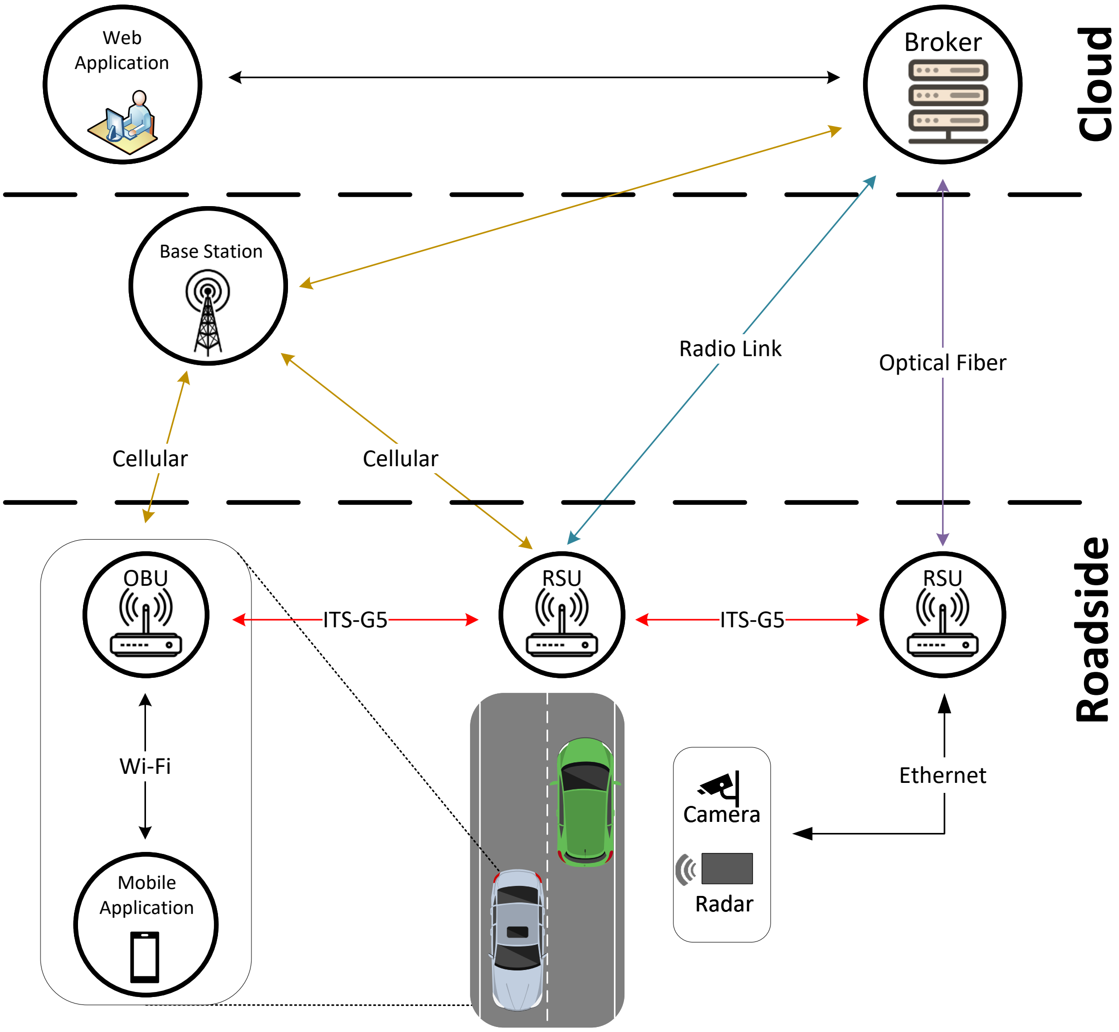


Figure 3.7: Overall system concept

CHAPTER 4

Implementation

This chapter exposes the hardware and software implementation used for the realization of this dissertation. It provides an extensive overview of the specifications and tools used to implement the work done.

4.1 HARDWARE

4.1.1 IT2S Platform

The IT2S Platform is a custom ETSI ITS-G5 station, characterized by its great flexibility and low-level control from both the hardware and software planes. It was developed in IT prior to this dissertation and it was used to implement, test, and validate the experimental work.

The platform is built upon the apu3 boards, a set of custom system boards dedicated to networking and embedded applications, developed by PC Engines that, among other interfaces, offers 2 mPCIe and 1 mSATA slots for expansion modules. For the IT2S, an SSD, WiFi, and LTE module (with the respective USIM card) are attached to the system board, as well as a pair of antennas for each one of the communication modules. Figure 4.1 shows an example of these boards where it is possible to see that the apu3d4 board (similar to the other versions of the board) has 3x1Gigabit Ethernet interfaces, 1 Serial interface, and 2 USB interfaces that can be used for configuration, maintenance, or communication purposes, enabling the fact that the platform can operate as an OBU or RSU with the ability to communicate with external hardware such as radars, sensors, cameras or GPS receivers.

In figure 4.2, on the right side of the IT2S platform, an external traffic radar is connected via Ethernet for external sensorization in the scenario that the platform operates as an RSU. This becomes a requirement when a given RSU is intended to disseminate messages with information about vehicles crossing the different lanes or stationary objects present in the carriage way inside the radar's field of view (CPMs). On the left side the ITS-G5 antennas are connected to the WiFi module while attached to the platform itself are the LTE antennas.

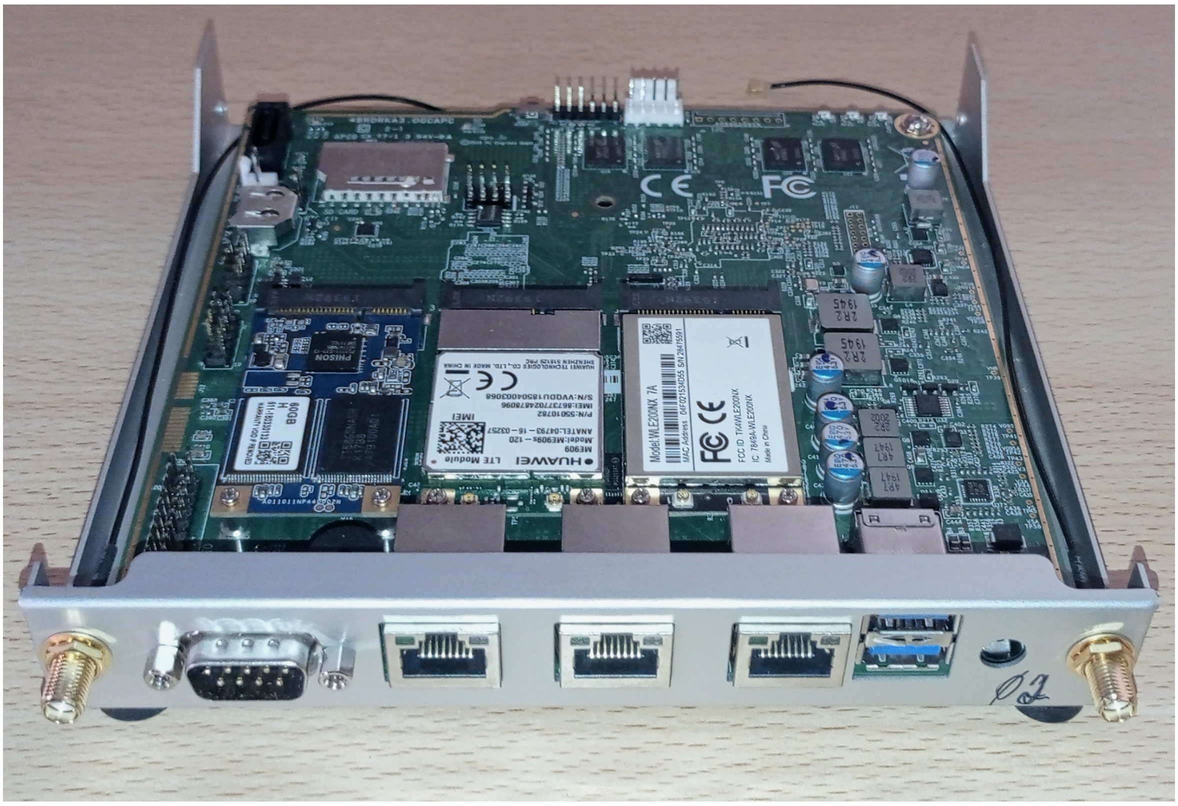


Figure 4.1: IT2S Platform without enclosure

(a) Laboratory configuration (IT2S platform and radar)

(b) Infrastructure configuration

Figure 4.2: IT2S platform scenarios

Parameter	**apu3d4**
CPU	AMD GX-412TC 4 cores @ 1Ghz
RAM	4GB DDR3-1333 DRAM
SATA Storage	60 GB
Power	12V @ 6 to 12W
Connectivity	3 Gigabit Ethernet channels
I/O	DB9, 2 ext.USB 3.0, 4 int.USB 2.0
Expansion	3 mPCIe, GPIO header
Board Size	152.4 x 152.4 mm

Table 4.1: System board specifications [98]

4.1.2 WiFi Module

The Compex WLE200NX is a full-size miniPCIe wireless network card (figure 4.3) making use of an AR9280 Qualcomm Atheros single chip, part of the Atheros XSPAN family chipset. With dynamic frequency selection and a maximum output power of 18 dBm (or 20 dBm for MIMO aggregation), it supports 5 GHz and 2.4 GHz wireless channels with a maximum data rate of 300 Mbit/s, when using spatial multiplexing MIMO and operating within a Wireless Local Area Networks (WLANs) in compliance with the IEEE 802.11n. Although with slighter lower rates, the wireless card is also fully backward compatible with IEEE 802.11a/b/g. The 2 antennas that makes up the 2x2 MIMO chain, can be connected to the card through small U.FL interfaces, and, for interference and power management issues, in compliance with IEEE 802.11h, Dynamic Frequency Selection (DFS) and TPC techniques are employed (useful for DCC power manipulation). In this matter the AR9280 also supports the ability of downshifting the 2x2 MIMO into 1x1 MIMO using a dynamic MIMO power save for the optimal balance of performance.

For security protocols, the module supports both Wired Equivalent Privacy (WEP) (with 64, 128 and 152 bit encryption) and Wireless Protected Access 2 (WAP) (IEEE 802.11i) while for authentication purposes the IEEE 802.11X specification is adopted. Other particularly interesting feature is the ability to allow the configuration of different parameters such as frequency, bandwidth and power levels in order to respect different regulatory domains of various countries (IEEE 802.11d Global harmonization standard) [99].

In its architecture, the AR9280 chip also features peripheral interfaces for General Purpose Input/Output (GPIO) connection as well as the use of a serial Electrically Erasable Programmable Read-Only Memory (EEPROM) for small storage and configuration purposes [100].

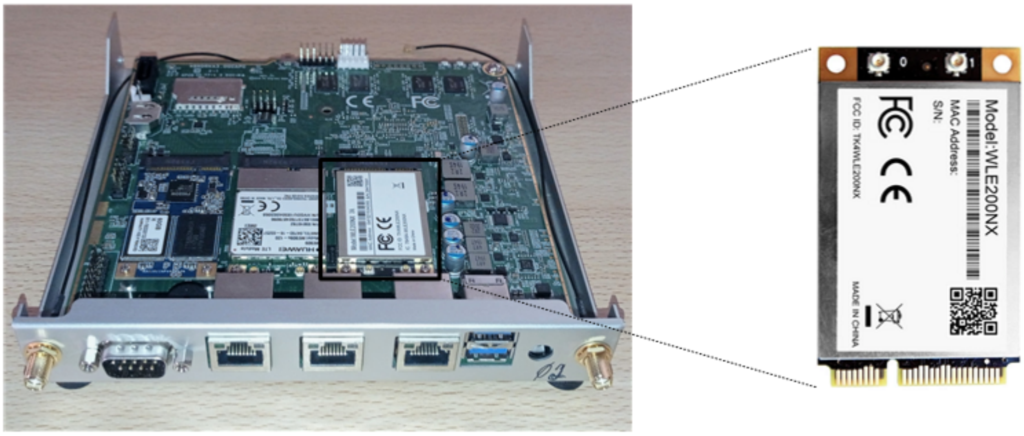


Figure 4.3: Wireless card Compex WLE200NX

Parameter	Unit	Description
Chipset	–	AR9280
Host Interface	–	mini PCI-Express 1.1 Standard
Operating Voltage	V(DC)	3.3
Maximum Power Consumption	W	2.7
Modulation Techniques	–	OFDM (BPSK, QPSK, 16-QAM, 64-QAM)
Frequency Bands	Ghz	2.4 and 5
Antenna connector	–	U.FL
Maximum data rate	Mbit/s	300
Temperature Range	ºC	-20 to 70
Dimensions	mm	50.95 x 30 x 3.2

Table 4.2: Compex WLE200NX specifications [99]

4.1.3 Cellular Module

The Huawei ME909s-120 is an LTE module developed based on the Huawei's HiSilicon chipset Hi6921M platform. It is the first of this family of chipsets that supports the fourth category of LTE UE across eight bands of Frequency Division Duplexing (FDD) LTE in Europe, Middle East and Africa region, and specially designed for Machine to machine (M2M) industrial applications that is, for example, vehicle telematics. The module is deployed with the Huawei land grid array standard design into the mPCIe that serves as interface for the control signals, power, UART, USB, USIM, audio and two antenna connectors. It provides additional features such as Communications Device Class – Ethernet Control Module (CDC-ECM), Firmware Over The Air (FOTA), sleep mode and Huawei extended AT command. The ME909s-120 can achieve a maximum transmission rate in the downlink of 150 Mbps and in the uplink 50 Mbps, using LTE FDD [101]. Table 4.3 presents a full specifications overview of the ME909s module when operating in the LTE bands [102].

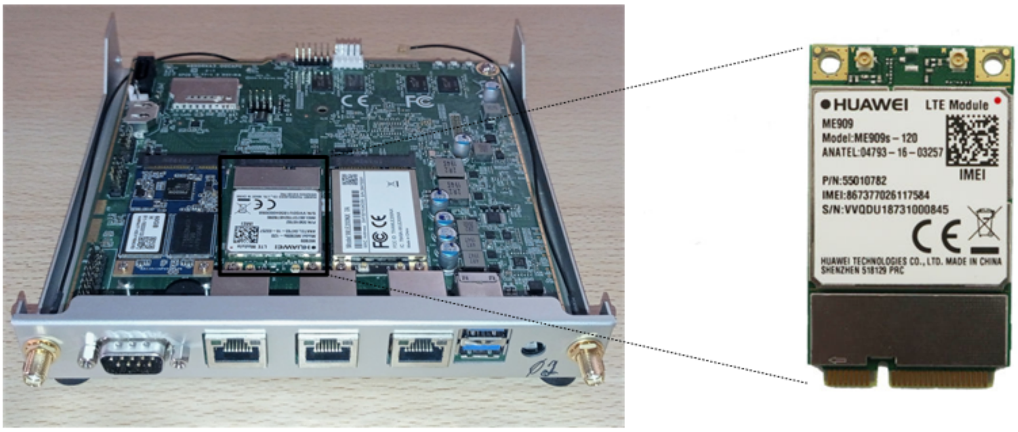


Figure 4.4: LTE Card Huawei ME909s-120 mPCIe

Parameter	**Unit**	**Description**
Operating Bands	–	B1/B2/B3/B5/B7/B8/B20, all bands with diversity
Operating Voltage	V(DC)	3.8
Output Power	dBm	23
Sensitivity	dBm	-102.2 to -101.1
Antenna connector	–	WWAN MAIN and WWAN AUX
Host Interface	–	mini PCI-Express 1.1 Standard
Maximum downlink data rate	Mbps	150
Maximum uplink data rate	Mbps	50
Temperature Range	ºC	-20 to 60
Dimensions	mm	50.95 x 30.40 x 3.52
OS Support	–	Windows8/10, WinCE, Android, Linux

Table 4.3: Huawei ME909s-120 specifications [102]

4.1.4 Radar

The UMRR-0C Type 42 is a traffic radar (figure 4.5) produced by smartmicro that operates in the 24Ghz band for multi-lane, multi-object traffic tracking, capable of measuring several parameters (such as range, angle and radial speed) of moving targets. With a bandwidth of 250Mhz and a maximum transmitted power of 20 dBm, the device uses a multiple Frequency Modulated Continuous Wave (FMCW) technique to acquire the relative speed and range of each target. The Type 42 integrated array of antennas is intended for long-range and wide horizontal coverage. It uses one antenna for transmission, eight receiving antennas, and it can detect up to 126 targets within its field of view. The radar also integrates tracking algorithms that can track up to 126 moving targets simultaneously with the help of features such as the 3D measurement (direct doppler, direct speed, direct angle) that is associated with every target, and the Ultra High Definition (UHD) resolution for an accurate refinement of the targets regardless of their speed, distance to the sensor or azimuth angle, making it suitable for high dense traffic scenarios.

The sensor delivers different data such as occupancy, vehicle headway, vehicle length, or average speed, offering the possibility to record data into an internal FLASH memory and thus operate in a fully standalone topology. Nevertheless, for direct real-time acquisition, the UMRR offers three data interfaces: a full duplex CAN 2.0B interface with a speed of 500 KBit/s, a RS485 interface with a speed of 921 KBit/s and a 10/100 MBit/s Ethernet interface [103] [104].

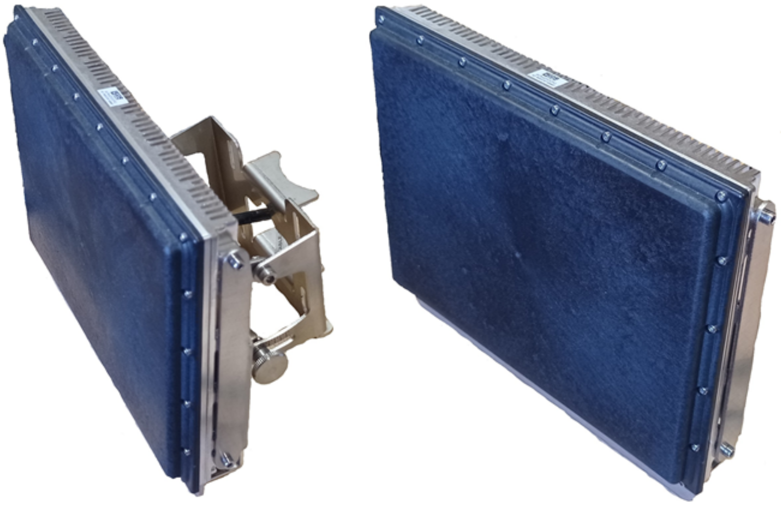


Figure 4.5: UMRR-0C Type 42 smartmicro radar

Parameter	Unit	Description
Frequency Band	Ghz	24
Interval Range	m	1.5 to 340
Interval Speed	km/h	-320 to 320
Azimuth field of view	º	-50 to 50
Elevation field of view	º	-8 to 8
Range accuracy	m	0.25
Speed accuracy	km/h	1
Angle accuracy	º	1
Power Supply	V	13 to 32
Ambient Temperature	ºC	-40 to 74
Dimensions	mm	212.6 x 154.6 x 31.65

Table 4.4: UMRR-0C specifications [103]

4.2 SOFTWARE

4.2.1 ITS-Station Configuration

To fully support vehicular communications, the IT2S platform should be able to not only operate within the ITS-G5 channel and power requirements but also to transmit and receive OCB packets. To achieve this level of customization, reliability and control over the system kernel and hardware, an Arch Linux distribution was installed. Arch Linux is an independently developed, general purpose lightweight GNU/Linux distribution that aims for a simple and minimalism operating system. It follows a rolling release model and is installed as a minimal based system in which the configuration is performed by the user, that installs only what is strictly required for a specific purpose, making it ideal for embedded scenarios and highly custom applications [105].

From version 3.19, the Linux kernel started to implement some changes to support 802.11p communications and OCB mode, so with the Arch Linux distribution installed (Linux kernel

5.11.16 and further), it is possible to access several tools and patches that will allow IEEE 802.11p communications with wireless cards that by default do not support IEEE 802.11p channel and power requirements, as it is with the Compex WLE200NX wireless card used in the IT2S platform. The Atheros AR9280 chip is supported by the kernel driver ath9k, that allows further configuration to operate within the 5.9 GHz frequency band with 10 MHz channels and OCB mode. To automate the process of applying these changes to every IT2S platform that will benefit from this card, two packages were design allowing the configuration to be done from a central office to all the RSUs and OBUs in the road environment at once, simply by downloading both packages. The first one is dedicated to the wireless module configuration, while the second configures the backhaul network interface (for RSUs), the *iptables* utility (discussed later in the chapter) and the Virtual Private Network (VPN) client (if needed).

The former package starts by getting PKGBUILD from the kernel source (to be used by the *makepkg* utility) and applying a custom patch that specifies each central frequency of the ITS-G5 channels and the OCB mode of operation to the ath9k driver. The Atheros module is then compiled and installed in every platform [1]. In the platform side, changes in the Linux wireless regulatory database are also made to allow 5.9 GHz channel tuning and OCB mode. The regulatory database specifies the allowed frequencies in different countries, with the intention to serve the Central Regulatory Domain Agent (CRDA), a user space agent [106] that builds the regulatory domain and sends it to the kernel that in a latter instance will enforce it to the ath9k driver [107]. An example entry of the regulatory database for Portugal (using the regdbdump tool) can be visualized in Code 1.

```
country PT: DFS-ETSI
        (2402.000 - 2482.000 @ 40.000), (20.00), (N/A)
        (5170.000 - 5250.000 @ 80.000), (20.00), (N/A), AUTO-BW
        (5250.000 - 5330.000 @ 80.000), (20.00), (N/A), DFS, AUTO-BW
        (5490.000 - 5710.000 @ 160.000), (27.00), (N/A), DFS
        (5725.000 - 5875.000 @ 80.000), (13.97), (N/A)
        (5850.000 - 5925.000 @ 20.000), (30.00), (N/A), NO-CCK, OCB-ONLY
        (57000.000 - 66000.000 @ 2160.000), (40.00), (N/A)
```

Code 1: Regulatory database entry example

Furthermore, a network configuration file is applied to the platform, specifying a fixed IP address (Code 2)[2]. The host part of the IP address will later be modified by the package installation process with the respective station ID assuring a unique address to each platform.

To finish the configuration process of the interface and successfully manipulate the configurations implemented by the patch to the Linux kernel code base and make them usable, the *iw* [108] configuration utility and *ip* [109] are used. While *iw* utility allows the user to manipulate the wireless devices configurations, the *ip* tool alters the network devices state as well as their routes. In this final step, the package executes a shell script where the commands are performed sequentially (Code 3).

---

[1] to accelerate the process this first steps can be done in a machine with greater processing capabilities

[2] wlp4s0 is the name of the Compex WLE200NX card within the system

```
[Match]
Name=wlp4s0

[Network]
Address=10.0.0.0/24
DHCP=no
```

Code 2: Wireless interface network configuration

```
1  #!/bin/sh
2  sudo ip link set wlp4s0 up
3  sudo ip addr flush wlp4s0
4  sudo iw dev mon0 del > /dev/null 2>&1
5  sudo iw reg set PT
6  sudo ip link set wlp4s0 down
7  sudo iw phy phy0 set antenna 1 1
8  sudo iw dev wlp4s0 set type ocb
9  sudo ip link set wlp4s0 up
10 sudo iw dev wlp4s0 set bitrates legacy-5 12 sgi-5
11 sudo iw dev wlp4s0 ocb join 5900 10MHZ
12 sudo iw dev wlp4s0 set txpower fixed 1000
13 sudo iw dev wlp4s0 set txpower fixed 1100
14 sudo iw dev wlp4s0 set txpower fixed 2700
```

Code 3: Package shell script

Among other commands, the script updates the regulatory domain to operate in Portugal (line 5), sets the wireless device to operate in OCB mode (line 8), sets the bit rate to 6 Mbit/s per 10 MHz channel bandwidth (line 10), uses the ITS-G5 control channel centered at the 5.9 Ghz frequency band (line 11) and finally leaves the transmission power at 2700 millibel-milliwatts (mBm) [3] (line 14), all in compliance with the ETSI standard defined in [44] [45]. When finalized, the package outcome can be visualized using the *iw dev* command (Code 4).

```
it2s-admin@it2s-itss-99 ~ $ sudo iw dev
phy#0
  Interface wlp4s0
    ifindex 8
    wdev 0x1
    addr 04:f0:21:53:4d:55
    type outside context of a BSS
    channel 180 (5900 MHz), width: 10 MHz, center1: 5900 MHz
    txpower 17.00 dBm
    multicast TXQ:
        qsz-byt qsz-pkt flows   drops   marks   overlmt hashcol tx-bytes        tx-packets
        0       0       8261    0       0       0       0       844071          8261
```

Code 4: Wireless interface information

To support LTE cellular modules, the Linux in-kernel *cdc_mbim* driver is used. The driver is intended to support USB devices that are in compliance with the “Universal Serial Bus Communications Class Subclass Specification for Mobile Broadband Interface Model”, a standard [110] optimized for mobile broadband devices and developed by the USB Implementers

---

[3] truncates the value to WiFi maximum power

Forum, a non-profit corporation that provides support for the adoption of USB technology and development of USB devices. *cdc_mbim* provides a userspace interface through the character device */dev/cdc_wdmX*, that is used by the user to grant access to the MBIM function control channel and the device. In spite of creating the channel, the driver does not participate in the device control and management, therefore applications such *mbim-network* [111] and *mbimcli* [112] are required. While the former is a simple network management of MBIM devices, the latter provides control over MBIM devices which includes triggering the connection over cellular network and getting module information. To initiate the connection a *mbim-network* configuration file (Code 5) is needed to, for example, specify the access point name, as well as to enable mbim-proxy option. After this initial setup a connection could be establish using a start command through the *mbim-network* application. Code 6 gives an example of the result from a query for a certain connection device (in the implementation the device is specified by the path */dev/cdc-wdm0*).

```
APN=internetm2m
PROXY=yes
```

Code 5: Mbim-network configuration file

```
[/dev/cdc-wdm0] Connection status:
              Session ID: '0'
        Activation state: 'activated'
        Voice call state: 'none'
                 IP type: 'ipv4'
            Context type: 'internet'
           Network error: 'unknown'
```

Code 6: Mbim connection query

4.2.2 Radar Configuration

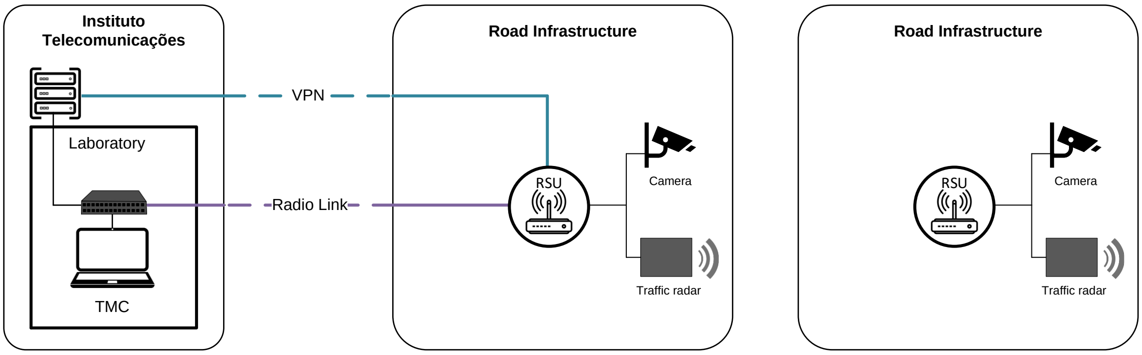
The radar is complemented by its own proprietary configuration software with the main purpose of serving the traffic center. TMC is a windows based software that allows configuration, monitoring, and logging data from all the smartmicro's UMRR sensors. The configuration starts by specifying the radar location based on the GPS coordinates and with this obtain a satellite view of the site (figure 4.6 shows the traffic of a station in Ponte da Barra). Furthermore, after specifying the right lanes and the sensor's position (elevation angle, azimuth angle, elevation) a Transmission Control Protocol (TCP) connection needs to be established between the radar and the TMC for the radar start sending data through the Ethernet cable. To achieve this, the information exchanged between the radar and the IT2S platform Ethernet interface connected to the radar must arrive to a windows machine running TMC. For this purpose, figure 4.7 illustrates the two possible configurations: in figure 4.7a the RSU reads and forwards the data to the machine where the TMC software is running, and on figure 4.7b the RSU reads the radar data and compose the CPM messages without the need to have the TMC software running in one machine. The latter configuration is important when the number of RSU scales. In order for the RSU to be able to forward packets, the *iptables* utility is used.

Object_Number	x_Point1 [m]	y_Point1 [m]	Width	Speed_x [m/s]	Speed_y [m/s]	Length [m]	Object_ID	Extended_Lane	Extended_class	cycles_cince_last	quality	ETA_to_mline [m/	relay
2	71.68	2.816	1.5	22.4	0.9	4.6	177	24	4	20	1.960784	0.4	615
3	75.008	5.76	1.5	27.3	0.9	4.6	178	37	4	12	4.313725	14	616
4	138.88	11.392	1.5	-28.4	-1.1	4.6	175	30	0	13	8.627451	3.6	64855
5	147.456	3.968	1.5	24.7	0.9	4.6	176	0	1	29	2.745098	18.8	615

Devices not equipped with Real Time Clock will keep date and time until next power cycle only.

☐ UMRR-2 2021.06.04 18:18

Figure 4.6: Traffic Management Configurator



(a) Connected to TMC

(b) Standalone

Figure 4.7: Possible RSU configurations

iptables is a command line utility for configuring the Linux kernel firewall, it is used to inspect, modify, forward, redirect or drop IP packets. The code that implements all these functions is built into the kernel and it is organized by a set of tables and predefined chains. Although *iptables* contains a much more complex structure since it contains five tables, only the *filter* and *nat* tables are commonly used for network address translation and firewall purposes. This simplified structure can be visualized in figure 4.8.

The IP packet arrives at the RSU Ethernet interface and passes through the different chains from top to bottom. If the packet is intended for the RSU, i.e it arrives at the first routing decision and goes through the left side of the chart, it stops at the *local process* to be consumed. In a similar way, if a packet is generated by the RSU it starts at the *local process* and gets to the bottom so it can be transmitted through the Ethernet interface. For forwarding the packets, only the *nat* table was modified. This table includes three chains: PREROUTING, POSTROUTING and OUTPUT, in which rules can be applied. Each rule consists of a predicate with several conditions and a corresponding action (namely *target*). If the packet satisfies all the conditions of a given rule, an action is taken upon the packet. The packet is subjected to the rules sequentially, so, in the case that a chain has two or more rules, the first rule were all the conditions are satisfied is the only one were the target is applied, meaning that the following rules will be ignored automatically. Code 7 represents an example of one configuration file implemented in a RSU.

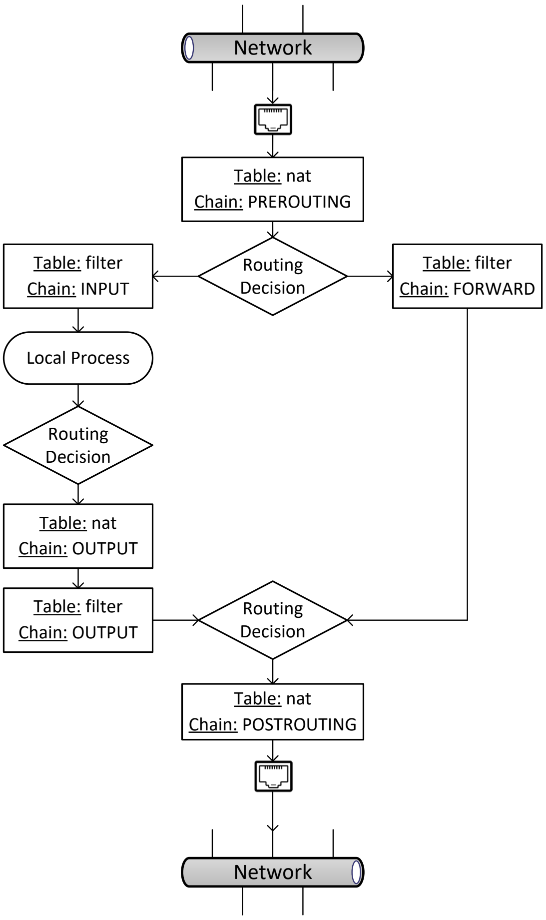


Figure 4.8: *iptables* simplified flow chart

From the first 5 lines it is possible to see that no rules were applied at the *filter* table and the corresponding chains, since the main goal was to modify the packet source and destination IP and not to filter (drop) any packets. In the *nat* table in the PREROUTING chain (line 12), every TCP packet that comes from the radar interface (enp2s0) to the corresponding TMC software destination port (55555), will be modified so that the destination IP address will become the computer in the laboratory that is running TMC (192.168.94.111). It is important to note that this is happening in the PREROUTING chain and thus, when the packet reaches the first routing decision (figure 4.8) it already has the modified destination IP, ergo the RSU knows that the packet is intended to other machine rather herself. For the POSTROUTING chain, any other packet that is intended to the RSUs network will be masqueraded (line 13). This is mandatory since the radar sends Address Resolution Protocol (ARP) packets before the TCP connection establishment. For packets that leave the RSU and are intended to the computer's laboratory, the source IP is modified to be the RSU's one, instead of the radar one (line 14). In the same way (line 15), the TCP packets that come from the computer's laboratory to the radar, must have the source IP of the Ethernet interface that is connected to the radar (the one that the radar thinks is communicating with).

```
1  *filter
2  :INPUT ACCEPT [0:0]
3  :FORWARD ACCEPT [0:0]
4  :OUTPUT ACCEPT [0:0]
5  COMMIT
6  
7  *nat
8  :PREROUTING ACCEPT [0:0]
9  :INPUT ACCEPT [0:0]
10 :OUTPUT ACCEPT [0:0]
11 :POSTROUTING ACCEPT [0:0]
12 -A PREROUTING -d 10.10.2.1/24 -i enp2s0 -p tcp --dport 55555 -j DNAT --to-destination 192.168.94.111
13 -A POSTROUTING -d 10.0.19.0/24 -j MASQUERADE
14 -A POSTROUTING -d 192.168.94.111/24 -j SNAT --to-source 10.0.19.7
15 -A POSTROUTING -o enp2s0 -p tcp -j SNAT --to-source 10.10.2.1:55555
16 COMMIT
```

Code 7: *iptables* configuration example

4.2.3 Collective Perception Service

Generation concept

With the information provided by the radar, it was possible to develop the CP sub-service and insert it into the facilities service of the ITS-S architecture (figure 3.1). Currently this sub-service only supports the radar from the RSU and it is not used in other radar for the OBU (for example). All sub-services are implemented using POSIX threads, allowing them to produce or interpret messages in a parallel way, independently from each other.

The initialization of the ITS-S services is done by reading a *toml* configuration file that contains several configurable parameters for each service. For the CP sub-service (Code 8), it is possible to control the CPM dissemination inside the period range defined by the ETSI standard [25], as well as the RSU Ethernet interface that the radar is connected to, the ip of that interface (previously configured in TMC) and to indicate if the radar is intended to be connected to the TMC software or not (figure 4.7).

Before starting the CPM generation if the radar is intended to establish a connection to TMC (4.7a), the sub-service is in charge of creating a raw listening socket in the Ethernet interface of the RSU to read the radar data. On the other hand if the RSU and the radar are

```
[facilities.cpm]
activate = false                    # Generation control of CPMs
rsu-obu-period-min = 100            # ms, minimum period between CPMs sent by both RSU and OBU
rsu-obu-period-max = 1000           # ms, maximum period between CPMs sent by both RSU and OBU
tmc-connected      = false          # boolean, is the ITS-S connected to the TMC?
radar-interface    = "enp2s0"       # string, interface that the radar is connected to
radar-ip           = "10.10.2.1"    # string, interface IP that the radar is connected to
```

Code 8: CPM configuration parameters

intended to work in a standalone manner (4.7b), the sub-service, in addition to create the raw listening socket, creates a TCP socket that establishes a connection with the radar so it can start transmitting data. After the TCP connection has been established the CP sub-service parses the data coming from the radar and builds the CPM. The CPMs are then part of the payload of the BTP data request and the facilities data indication SDUs (figure 3.1) , where the headers are built according to the type of ITS-S, message and dissemination. The messages that are sent to the applications layer by the facilities data indication are redirected to the cloud MQTT broker and could be visualized in the web application (figure 4.9). The ones sent to the transport layer by the BTP data request are sent through ITS-G5 (Atheros WiFi card).

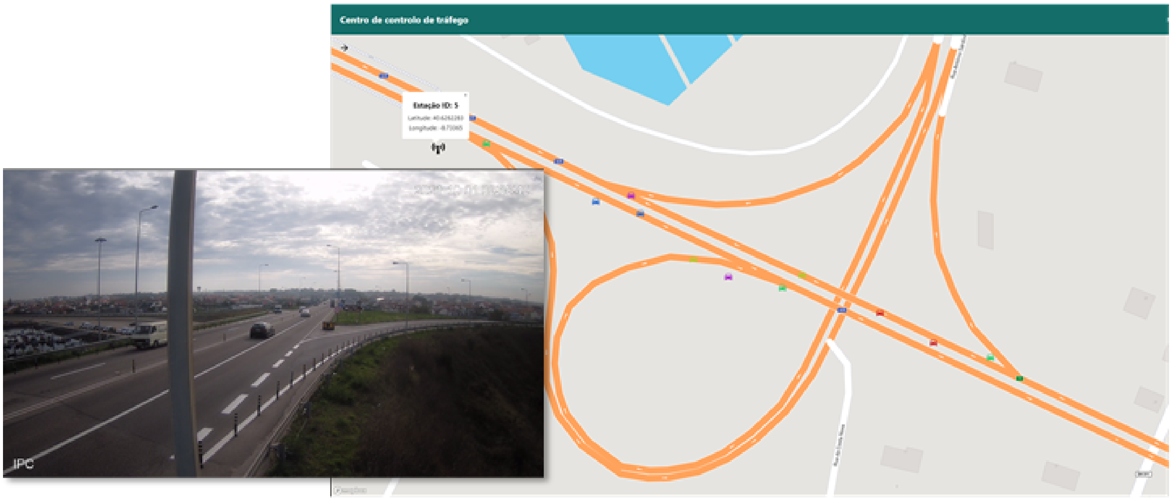


Figure 4.9: Web application displaying the data from the CPMs

Dissemination concept

Besides the maximum and minimum period of CPM generation, [25] also defines some rules to prevent channel overload and avoid redundancy of some objects. The principle is to include fewer times the most static objects and more times the most dynamic ones. Currently it is the only criteria to include or not an object into a CPM since the UMRR-0C Type 42, does not give all the information needed to classify the objects or to calculate the free space confidence between the object and the ITS-S (provides the free space between the sensor and the detected object, and the confidence level is defined as ratio of the number of detected evidences of free space with respect to the total number of detection attempts). Taking all this into consideration, it was applied some frequency management rules regarding perceived object inclusion and sensor information inclusion into the CPM dissemination process:

- For the sensor inclusion information, the CPM should include the Sensor Information Container [4] whenever the time passed since the last CPM that included the Sensor Information Container is greater or equal to 1000 ms.
- For the perceived object information, an object should be included in a CPM if:
  - It has first been detected by the radar after the last CPM generation event.
  - The absolute euclidean distance between the current estimated position of the reference point of the object and the estimated position of the reference point of this object lastly included in a CPM exceeds 4 m .
  - The difference between the current estimated absolute speed of the reference point of the object and the estimated absolute speed of the reference point of this object lastly included in a CPM exceeds 0.5 m/s .
  - The difference between the orientation vector of the current estimated absolute velocity of the reference point of the object and the estimated orientation vector of the absolute velocity of the reference point of this object lastly included in a CPM exceeds 4 degrees.
  - The time elapsed since the last time the object was included in a CPM exceeds *rsu-obu-period-max* (Code 8).

To implement these rules, the following flowchart (Figure 4.10) demonstrates the process of CPM generation. After the CPM trigger event, the ITS PDU header is filled with the corresponding data elements. A dedicated timer evaluates if the interval period has passed for the CPM to include the *SensorInformationContainer*. For the *PerceivedObjectContainer* an array with a length of the maximum number of possible detected objects by the radar is created. This array, will serve as a checking reference to if an object was included in a previous CPM and thus comparing its previous status (that were disseminated in the last CPM the object was included) with its current status. When an object is included in a CPM, the array index that corresponds to the object ID will be put in state of 1 and when an object leaves the radar LOS, state of 0. This way, the object present in the list detected by the radar is only submitted for comparison if the state of the array is 1 avoiding unnecessary computation.

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[4] looking back at figure 2.6

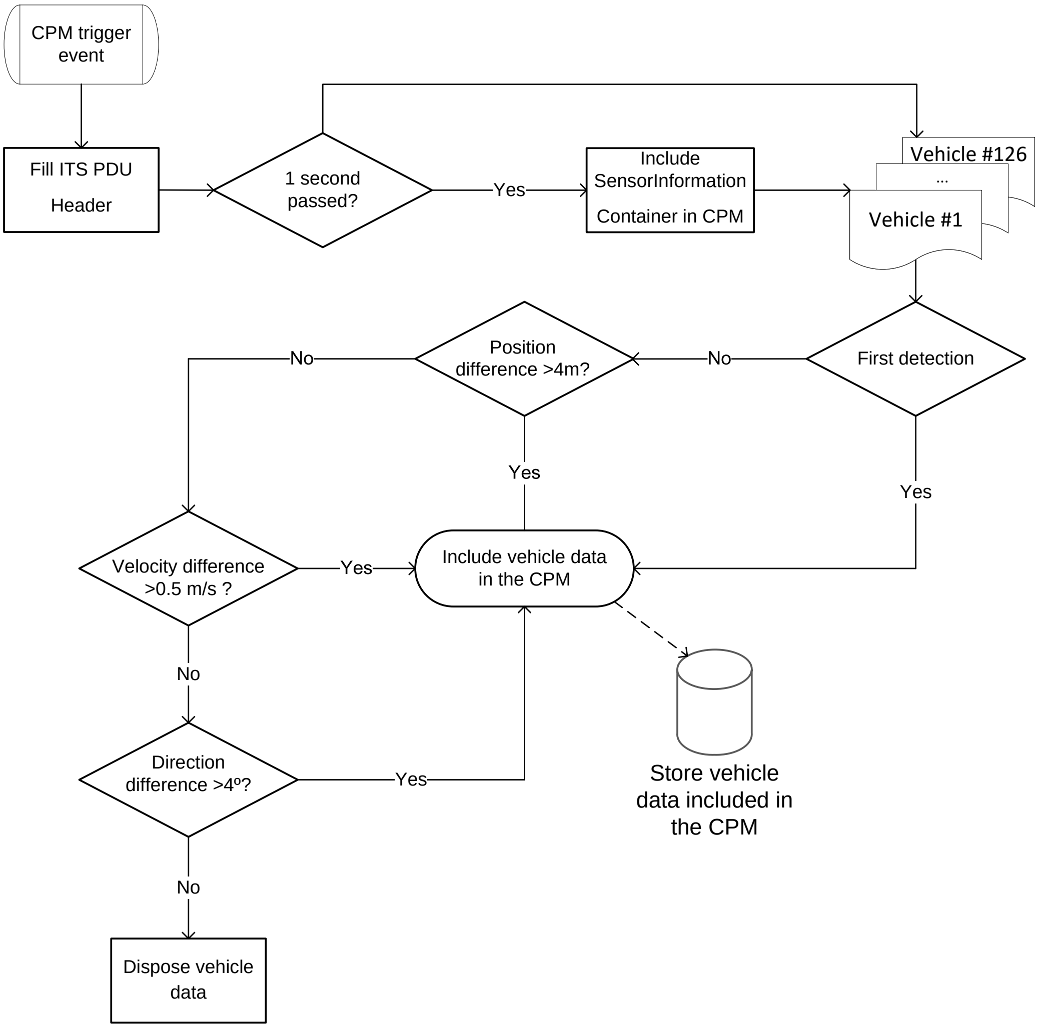

Figure 4.10: CPM inclusion rules flowchart

4.2.4 On-Board Unit configuration

As shown before, the IT2S platform can operate as an OBU or an RSU since the same architecture is used with slightly variations on treating applications and sub-services like the CA and DEN basic services. In the same way the CP sub-service is configured, the *toml* configuration file also indicates the type of ITS-S that the IT2S platform should behave like. Using a Mosquitto message broker, a local broker is created in the IT2S platform, in which is later used to communicate with the mobile application using a WiFi connection [5]. Similar to the ITS-G5 wireless module configuration and the backhaul network interface configuration for the RSU, a package to automate the process of configuring an wireless access point, using a WiFi adaptor, was created. The package starts by specifying a set of *udev* rules (Code 9) that are triggered whenever a WiFi adaptor is plugged in and the adaptor satisfies one of the rules. If the rule is triggered, the WiFi adaptor name changes within the system. This becomes important when we have a range of WiFi adaptors and want to standardize their

---

[5] only when the platform is operating as an OBU

name within the system.

```
## D-Link
SUBSYSTEM=="net", ACTION=="add", ATTRS{idVendor}=="2001", ATTRS{idProduct}=="331b",
ATTR{address}=="00:ad:24:15:*:*", NAME="it2s_wifi"

## ASUS
SUBSYSTEM=="net", ACTION=="add", ATTRS{idVendor}=="0b05", ATTRS{idProduct}=="17ba",
ATTR{address}=="f8:32:e4:b4:*:*", NAME="it2s_wifi"

## Realtek
SUBSYSTEM=="net", ACTION=="add", ATTRS{idVendor}=="0bda", ATTRS{idProduct}=="8176",
ATTR{address}=="00:13:ef:*:*:*", NAME="it2s_wifi"
```

Code 9: Udev rules for the WiFi adaptors

To create the wireless access point, the *hostapd* software utility detects and configures the wireless adaptor with the same Service Set Identification (SSID) as the IT2S platform hostname. To take advantage and not limit the wireless access point to the connection between the mobile phone and the local MQTT broker, and to download the maps for the mobile applications, the package also enables an internet connection through the wireless adaptor. Similar to the *iptables* configuration done in Code 7, the traffic is redirected from the wireless access point interface and the cellular communications module providing an internet hotspot, for example in a moving vehicle.

For the OBU to receive data from a specific area of interest beyond ITS-G5 range, it was implemented a feature that in addition to its own topic (based on the its location), the OBU subscribes to all the adjacent topics that redirects the messages published into that group of topics to the local MQTT broker. This way, through the cloud MQTT broker, the OBU receives messages in advance, and the user through the mobile application, can visualize the message information in his smartphone. With this feature it is possible to also disseminate CAMs, and DENMs (created by the mobile application) via ITS-G5 and via cloud MQTT broker, providing the road operator with important information and creating a certain level of dissemination redundancy.

In figure 4.11, at the left side, it is possible to see in the camera footage that the cars in the green circle are crossing the van in the red circle. The CPM generated by the RSU in the blue circle (the car in the right side of the RSU represents the OBU with a simulated GPS coordinates) are transmitted to the cloud MQTT broker and visualized by the web application. Since the blue circle car is simulated to be near the RSU it will subscribe to the topic where the CPMs are being published. The OBU redirects the messages to its own local MQTT broker and through the mobile application the user can see the surrounding information (in the mobile application the cars illustrated by the CPMs have the same orientation although having different traffic flow directions). The importance of this feature is more evident when the OBU is not on the range of an ITS-G5 dissemination and receives information from an area of interest through the cloud MQTT broker by subscribing to adjacent topics.

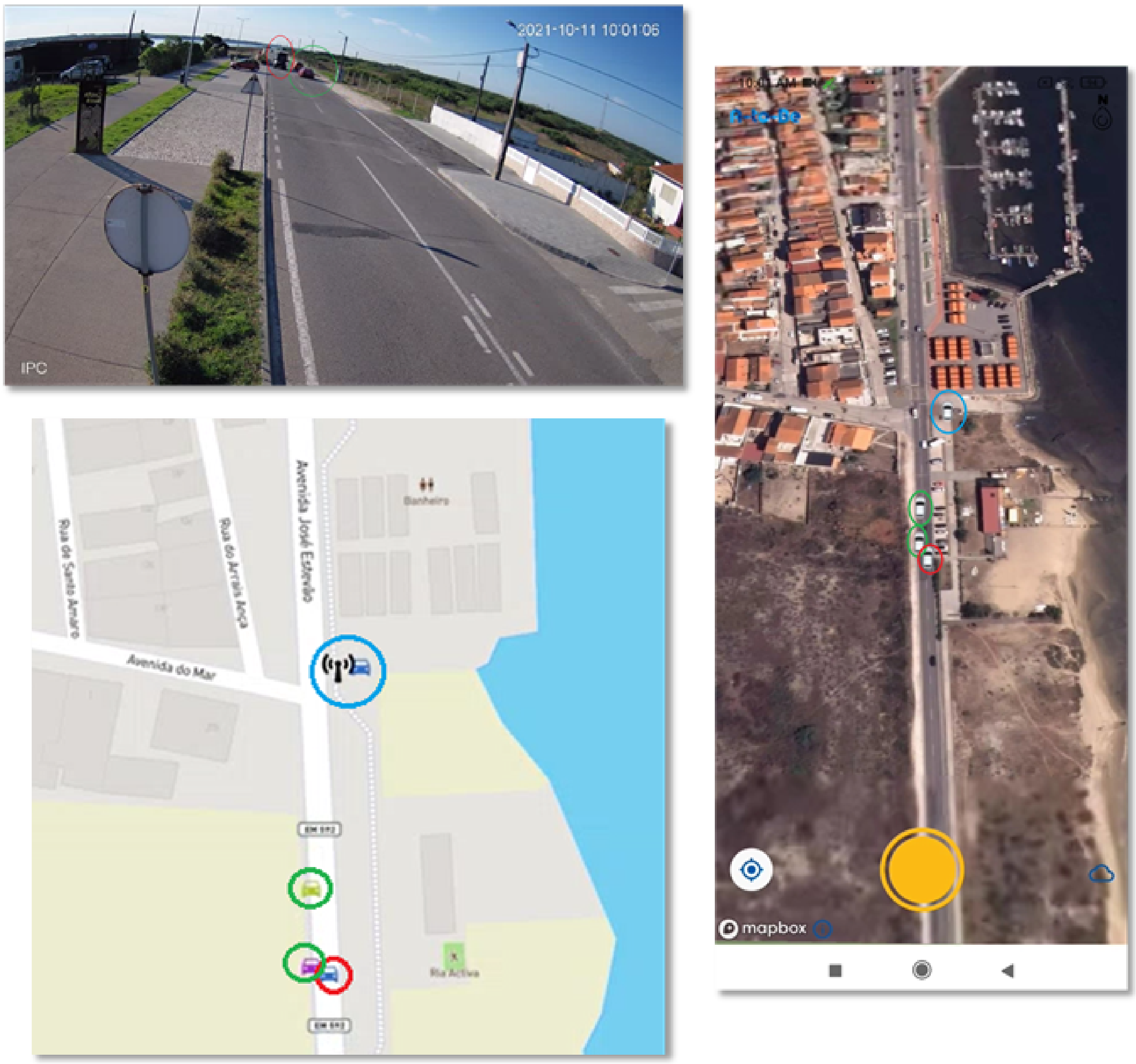

Figure 4.11: Visualization of CPMs in the mobile application

4.2.5 Platform installation

In terms of installation, all the RSUs are sealed in exterior waterproof electrical boxes that protect the equipment from weather conditions. Besides the RSU, the electrical boxes hold a switch and power outlet, fed by the electrical grid. The switch provides the connection between the RSU, radar, IP camera and public WiFi access point that provides internet connection. All hardware and communications infrastructure were already installed by the PASMO platform [113], a project developed in IT for mobility solutions development and experimentation. Even though the infrastructure was implemented, in-field interventions were needed to all the RSUs mainly to implement and configure the architecture, replace some damaged material, configure the radar and to establish access to IT (figure 4.12).

For three of these stations, the main internet access is made through a radio link with direct communication to IT, that passes through an antenna installed at the top of a radio tower TerraNova located at Gafanha da Nazaré (figure 4.13), giving not only internet access to the public access point but also direct access to the network formed by these stations for configuration purposes (e.g., via Secure Shell (SSH)). For the others stations, (figure 4.14) the main internet access is made through optical fiber to the public network, that, for configuration and remote access purposes, has a VPN connection to the IT network. In addition to the radio link and optical fiber approaches, the RSUs also have at their disposal an LTE module and a respective Universal Subscriber Identity Module (USIM) card that adds some redundancy in case of connection failure.

Figure 4.12: Interventions in the infrastructure

Figure 4.13: RSUs installed with a radio link connection

Figure 4.14: RSUs installed with a fiber connection

CHAPTER 5

Tests and Results

This chapter exposes the results from the tests performed to evaluate and validate the implementation of the system. Firstly, to explain the reasons behind the performed tests, the evaluation metrics are presented. After, the results from the tests are illustrated and finally discussed in the end of the chapter.

5.1 Test metrics

As the main motivation behind ITS relies on safety-critical use cases, the main issue to address is time delay. As traffic efficiency and infotainment applications tend to be more tolerant to delay, safety-critical applications performance and utility tend to diminish when certain time constraints are not met. The Collective Perception Service needs to maintain delay values to the bare minimum since cooperative and automated vehicles rely on the most updated information to perform maneuvers or make decisions. These delays could be associated with the time that information needs to travel the communication channel or/and the computation time that takes for the information to be processed and travel between the layers of the ITS-S architecture. For example, as mentioned in Chapter 2, in CAM generation [20], ETSI defined a maximum delay for the facilities layer to deliver the information to the networking & transport layer of **50 ms** and since such constraint was not defined for the CPM generation standard, this value is going to be taken as a reference for the tests performed. The BSA [15] also defines a maximum latency value for safety-critical applications of **100 ms** and for least priority ones **500 ms**. Another key issue to be taken into account is the amount of traffic load injected into the communication channel. Although not representing a problem in small experimental tests, in large and overpopulated environments every step towards mitigating this issue while maintaining the overall system's performance is important. Mechanisms such as the Decentralized Congestion Control (DCC) and the dynamic generation frequency of CAMs and CPMs try to maintain a balanced traffic load by reducing the redundant and unnecessary information as much as possible, or at least control it.

5.2 Test setup and methods

To evaluate the implementation done in this work, and taking into account the metrics introduced before, the tests focused on measuring the communication delay between two IT2S platforms. The tests include the time that it takes for the message to be delivered for transmission in the access service and the time it takes for a packet to travel along the communication channel. Another set of tests will be focused on the amount of data that is delivered to the ITS-G5 channel based on the dynamic rules applied in the generation of the CPM messages, this way, it will be possible to evaluate the impact of these rules in different traffic scenarios.

The experimental setup built at the laboratory (figure 5.1), consists of two IT2S platforms equipped with two antennas for the ITS-G5 module and other two for the LTE module (similarly to what is shown in figure 4.2). One platform, acting as an RSU, is connected to a radar for message generation purposes, while the second one acts as an OBU, simply to receive messages via ITS-G5 or through the cloud MQTT broker.

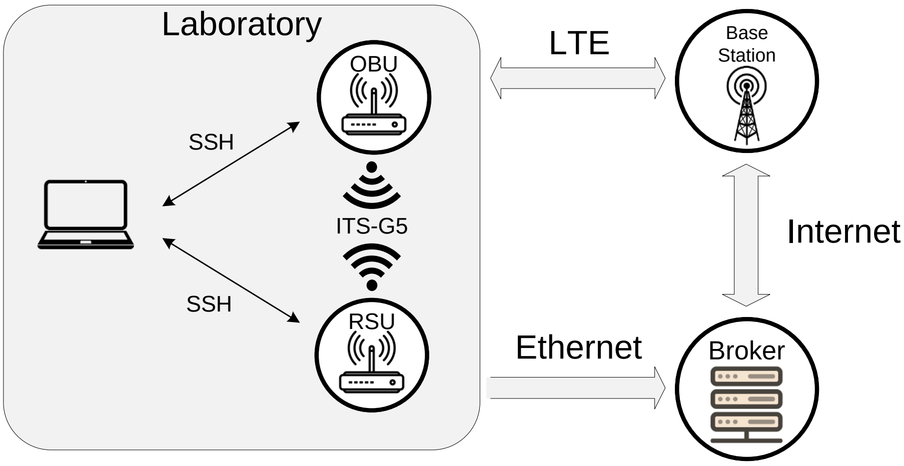

Figure 5.1: Test setup schema

As showed before, the TMC software main purpose is for configuration and visualization of data, however one more useful feature implemented and used, is the simulation mode where it is possible to simulate traffic on the defined road lanes. To generate the CPMs for the different tests, the radar is connected to a computer running the TMC software (figure 5.2). Since the real traffic data generated by the road infrastructure was only moderate at certain periods of the day, the simulation mode of TMC provided the necessary traffic density manipulation to perform the tests. The data produced by the simulation and the infrastructure radar are the same, therefore, this way it is possible to create a personalized real road scenario.

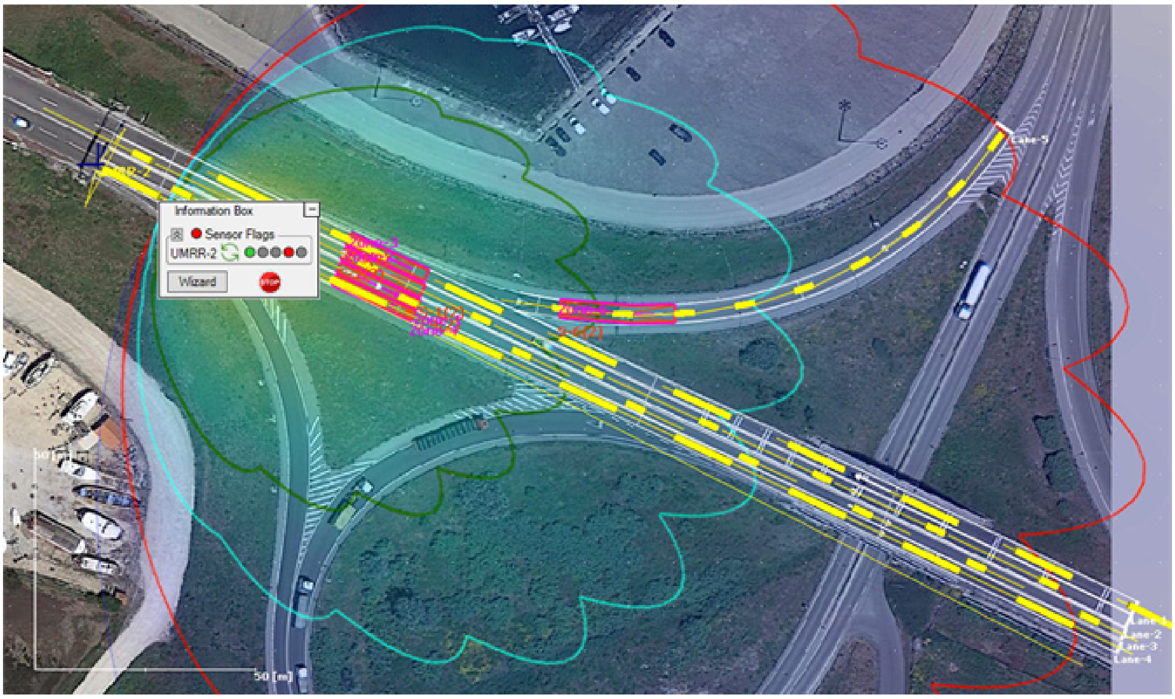

Figure 5.2: TMC in simulation mode

Another important aspect in measuring timestamps between platforms is to ensure time synchronization, achievable by several network protocols, being them the most known: the Network Time Protocol (NTP) and the Precision Time Protocol (PTP). The PTP [1] uses a master/slave architecture, where the master (synchronized to an accurate time reference such as a GPS) exchange synchronization messages with the slaves. This provides the precise time from the master, as well as the network delay between both ends, giving a nanosecond precision when using the correct network architecture, compliant with IEEE-1588 standard [115]. The NTP has a server/client approach, where the clients query the server for a Universal Coordinated Time (UTC) time reference and the server responds to the queries with a timestamp of its own response. The client determines the network latency based on the query delay and adjusts its internal clock accordingly. The resulting accuracy of the NTP can vary depending on the scenario where the Local Area Network (LAN) case can achieve accuracy in half of a millisecond, the Wide Area Network (WAN) can achieve 10 milliseconds in the best case scenario [116].

For the tests performed on the implementation, the NTP approach was used since the University of Aveiro provides access to its own NTP server and the accuracy obtained by this synchronization method was enough for the time delay needed to be measured. This implies that a connection to the campus network is necessary to reach the NTP server with low delay queries and assure the precision needed. This case is more relevant when communication is done by cellular LTE, in which an Ethernet connection is always used to reach the NTP server. In the road environment such issue can be solved by retrieving the time by the GPS

---

[1] The PTP is also widely known as the IEEE-1588 standard [114]

module to assure synchronization between all the ITS-Ss. The tests were based on simulating a different number of vehicles and register the different timestamps and packet sizes along the communication chain of the CPMs. Moreover, the dissemination interval within the boundaries defined by ETSI, was also tested for the different simulation scenarios, giving an overview of the system performance for a high and low demanding scenarios.

5.3 EXPERIMENTAL TESTS

5.3.1 Inter-layer delay

The first group of tests performed analysed the time delay produced by deliver the CPMs from the facilities service to the access service. Every time a CPM is produced, a timestamp is recorded in the same way as when the message reaches the access service and is ready for transmission (equation 5.1).

$$t_{total}(k) = t_{access}(k) - t_{CPS}(k), k \epsilon [1, 10000] \tag{5.1}$$

For this set of tests, the number of simulated vehicles (10, 20, 30, 40, 50, 60, 70, 75), as well as the time interval of CPM generation, was varied (200ms, 400ms, 600ms, 800ms, 1000ms). Since the length of the SDUs of the architecture is defined as 2048 bytes, the current maximum number of vehicles detected cannot exceed 75, to build a well defined CPM. For each number of vehicles simulated, 10000 CPMs were produced. The mean delay value from the collected timestamps was calculated resulting in the data set illustrated in figure 5.3.

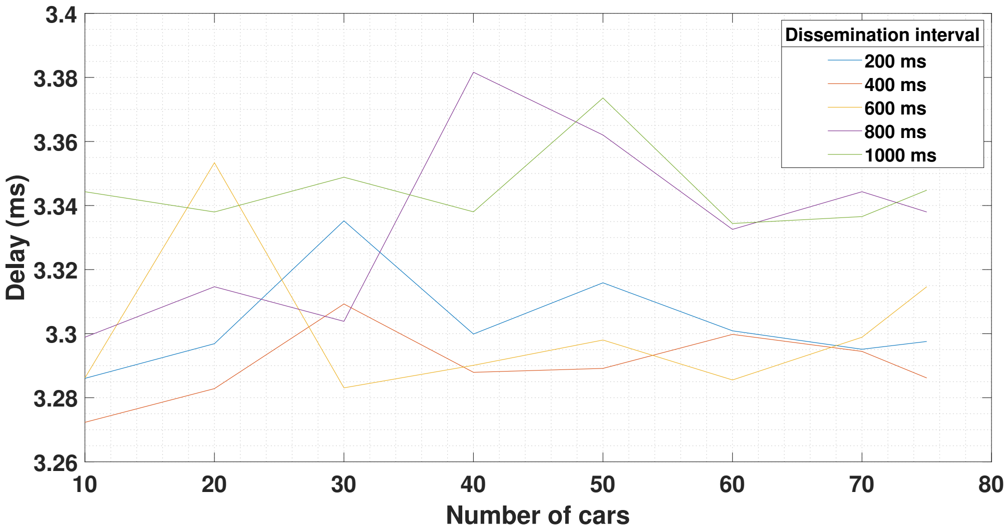

Figure 5.3: Inter-layer time delay

As the number of vehicles increases, the amount of data produced by the radar also increases, leading to possible buffer congestion in the inter-process communication sockets. Since the encapsulation and treatment of the CPM in the different services is transparent to the size of the payload produced in the upper layers, the delay should be maintained independently of the amount of data produced in the facilities layer. Although some fluctuations in the time values are observed, these are negligible since the difference between the maximum and minimum delay of a single dissemination interval, or even between the various dissemination intervals, does not exceed 1ms.

5.3.2 Channel load

This group of tests evaluate the efficiency of the dynamic generation rules and verify the amount of data injected in the channel by the CPS. Similarly to the previous set of tests, various numbers of vehicles, as well as generation intervals, were tested. However, instead of producing a predefined number of messages for each combination of vehicles and generation intervals, one hour of simulation was ran. At the access layer, the number of bytes sent through ITS-G5 was measured, meaning that these values include the headers added by the intermediate layers before transmission through ITS-G5 (equation 5.2).

$$T = \frac{\sum_{t=1}^{3600} n_{CPM} + n_{GeoNetworking} + n_{BTP} + n_{MAC} + n_{LLC}}{3600} \tag{5.2}$$

The total number of bytes taken by the tests for the static generation rules and for the dynamic generation rules can be visualized in figure 5.4 in 5.5 respectively.

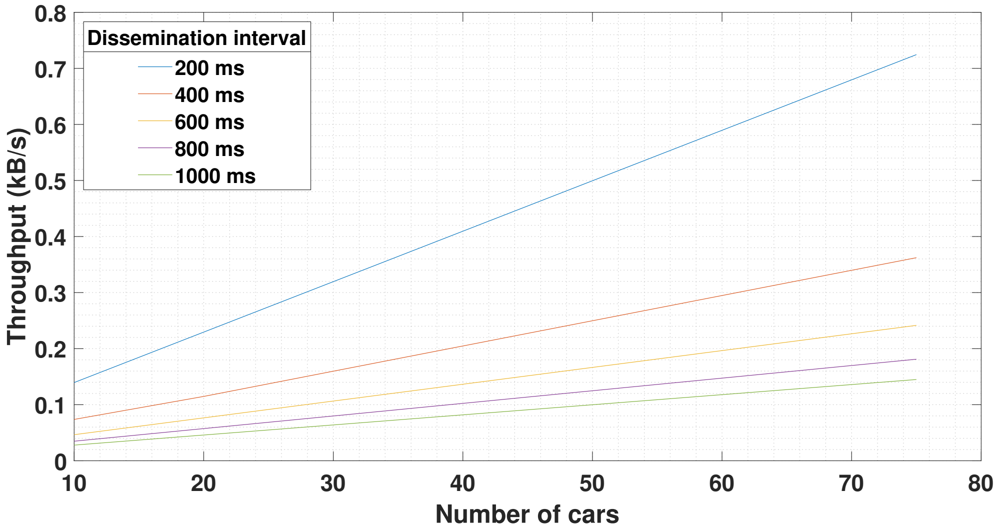

Figure 5.4: Number of bytes produced by static generation

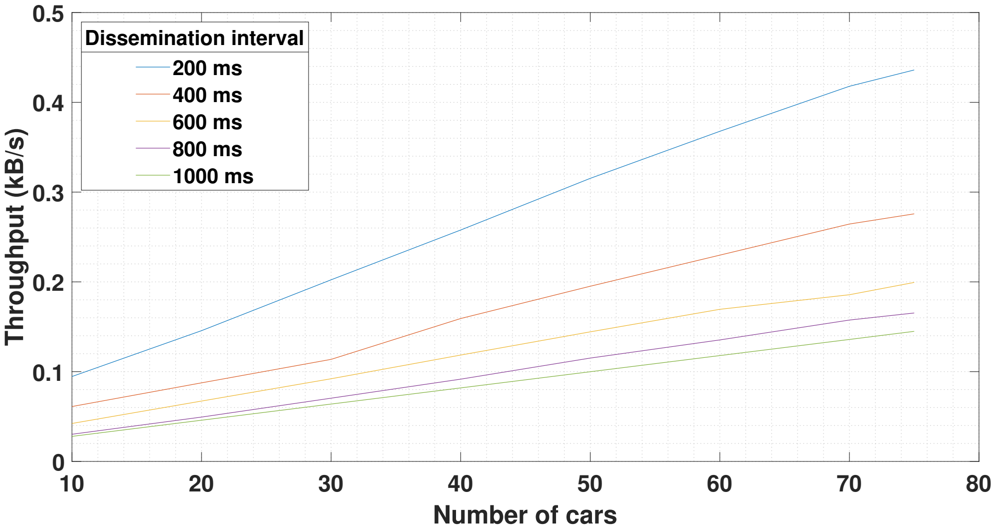

Figure 5.5: Number of bytes produced by dynamic generation

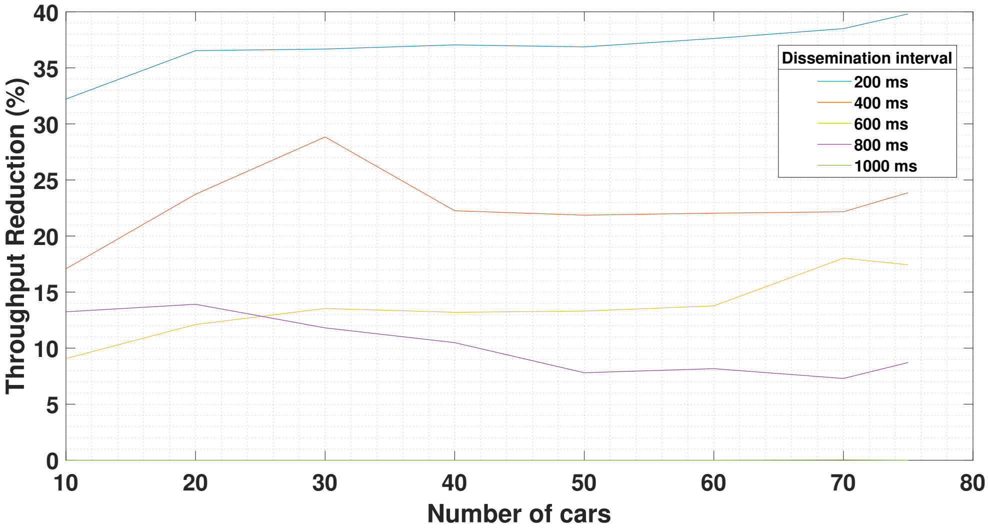

Figure 5.6: Difference in number of bytes produced by both rules

In the static generation rules, the increment in the number of cars is translated into a linear increase in the amount of data transmitted by the RSU. In the dynamic generation rules, the same linear tendency is verified, although it is equivalent to a much lower throughput. While the difference in the number of bytes between rules is almost zero in the 1000ms interval (figure 5.7 and figure 5.6) (since at this dissemination interval at least 1 rule is already satisfied and thus all vehicles are included in the message independently of their dynamics), the remaining ones present a smaller number of bytes transmitted for all number of simulated vehicles. The rules effect is more evident in the 200ms interval since the vehicle dissemination rules are harder to satisfy within a smaller time window, hence some vehicles are excluded in consecutive CPMs reaching the maximum troughput reduction of 40% in the most demanding scenario tested.

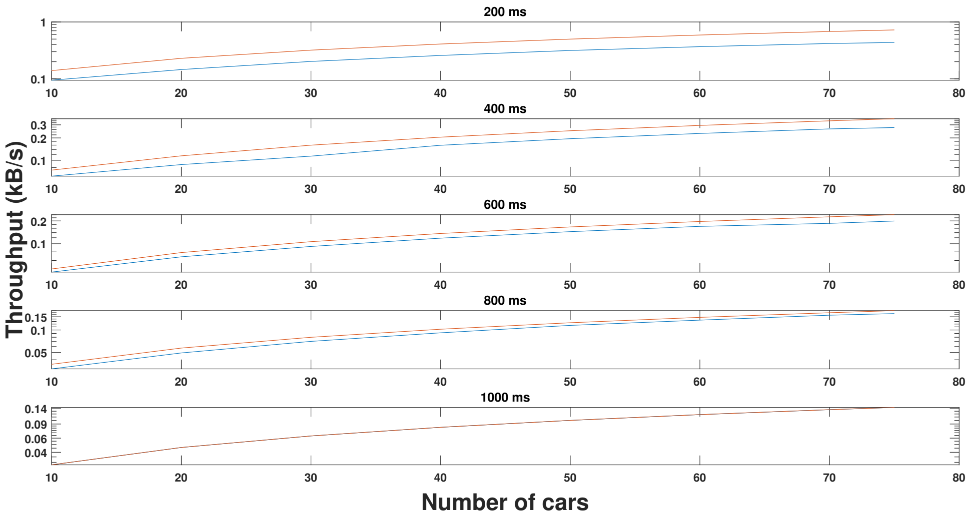

Figure 5.7: Difference between each dissemination interval

5.3.3 End-to-end delay

The last group of tests focused on measuring the mean end-to-end delay between a transmitting ITS-S (this case an RSU) and a receiving ITS-S (this case an OBU). The same criteria was taken into account (10000 messages for different number of cars and dissemination intervals) for three different delay measurements: the first one measures the delay between two ITS-Ss platforms using ITS-G5 (figure 5.8 to 5.10):

$$t_{total(ITS-G5)}(k) = t_{rxOBU(Access)}(k) - t_{txRSU(Access)}(k), k \epsilon [1, 10000] \tag{5.3}$$

The second one measures the delay when the RSU uses an Ethernet connection to publish the CPMs in the MQTT broker and the OBU uses an LTE connection to subscribe and receive the messages (figure 5.11 to 5.13):

$$t_{total(ETH-LTE)}(k) = t_{rxOBU(Applications)}(k) - t_{txRSU(Applications)}(k), k \epsilon [1, 10000] \tag{5.4}$$

Finally the third measures the delay when both the RSU and the OBU use an LTE connection to access the broker (figure 5.14 to 5.16)

$$t_{total(LTE-LTE)}(k) = t_{rxOBU(Applications)}(k) - t_{txRSU(Applications)}(k), k \epsilon [1, 10000] \tag{5.5}$$

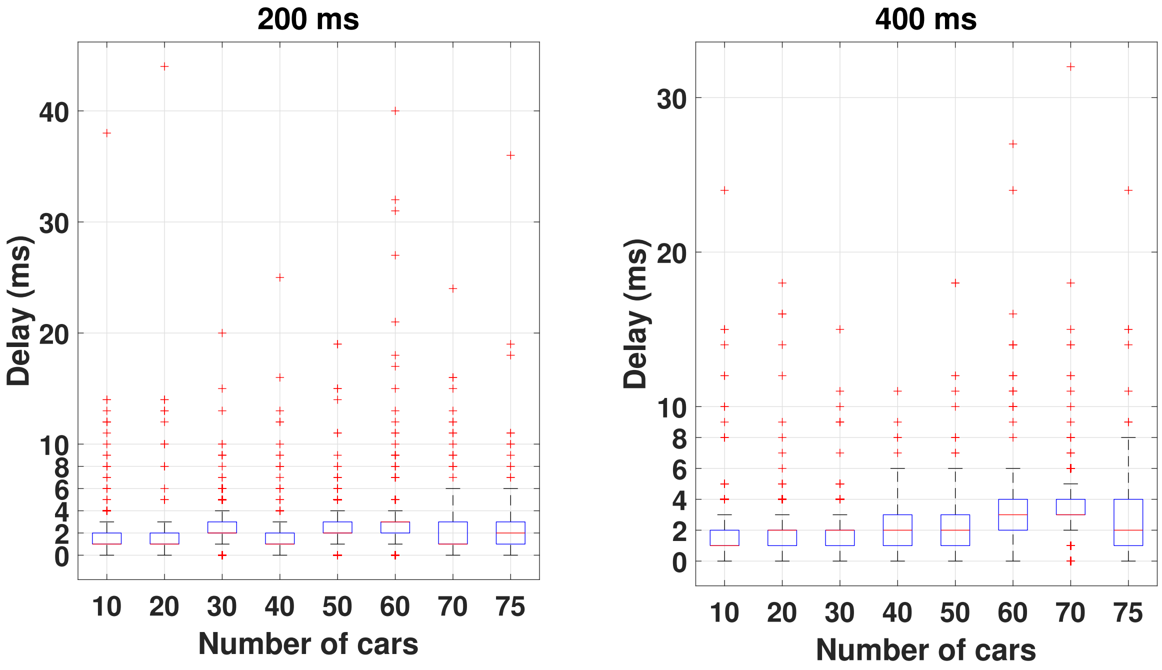

Figure 5.8: 200ms and 400ms dissemination intervals for ITS-G5

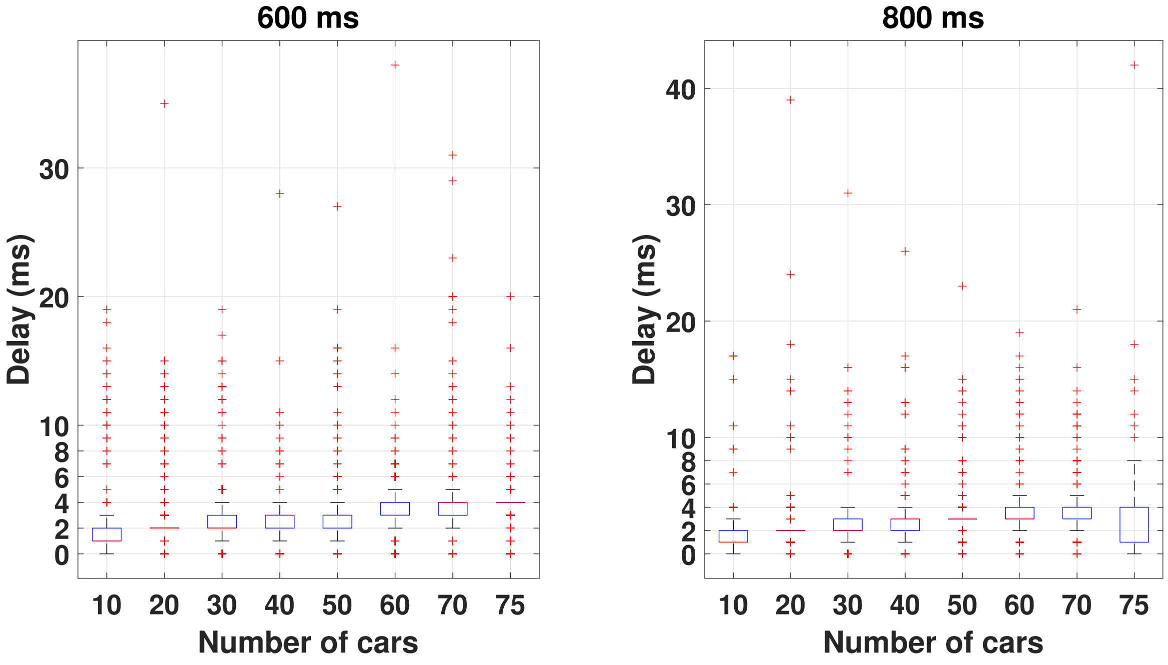

Figure 5.9: 600ms and 800ms dissemination intervals for ITS-G5

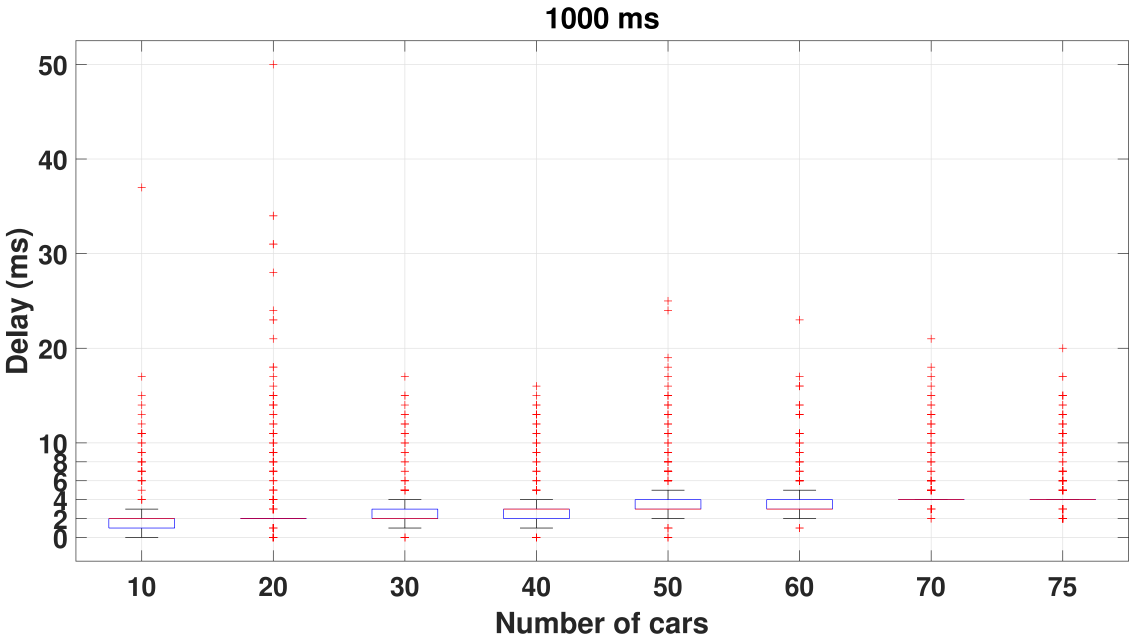

Figure 5.10: 1000ms dissemination interval for ITS-G5

The presence of a higher number of cars and the subsequent larger packets tend to increase the delay in the communication channel. This fact is visible at the 200ms, 400ms and 800ms intervals where larger *whiskers* show that values measured vary more, or in the 600ms and 1000ms where the average value is higher. Moreover, in general, the *outliers* (individual points in red) have sporadic values greater than 20ms, although, a higher concentration of these points is located near the upper and lower values of the *whiskers* indicating that the delay does not oscillate so much from the values defined by the box plot.

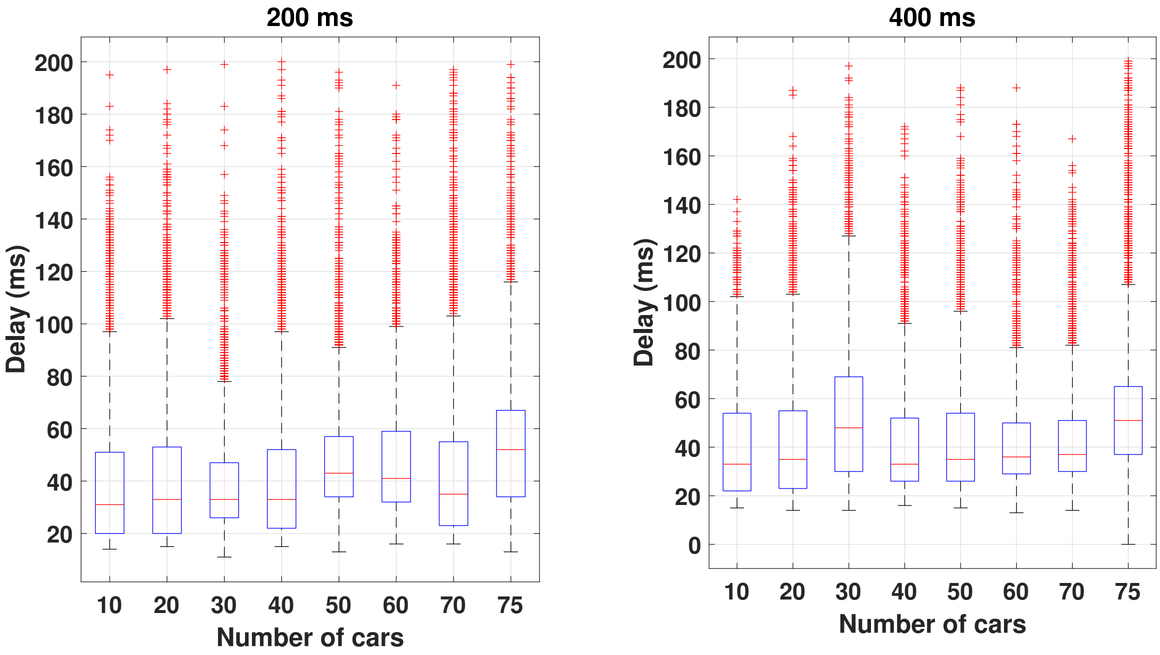

Figure 5.11: 200ms and 400ms dissemination intervals for Ethernet and LTE

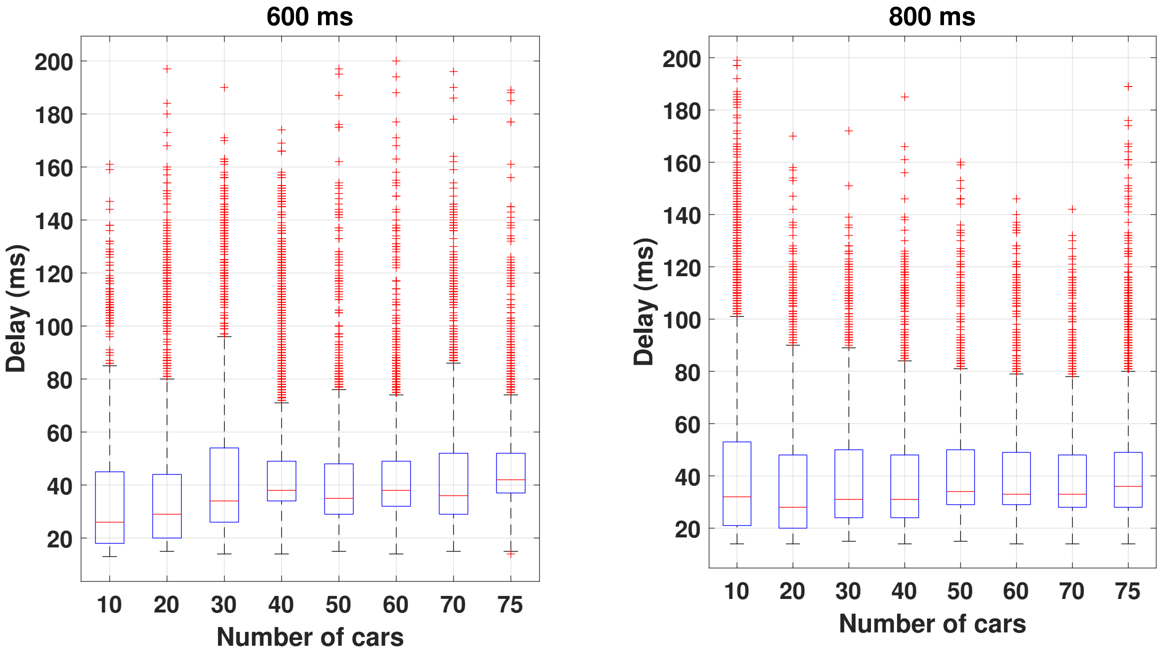

Figure 5.12: 600ms and 800ms dissemination intervals for Ethernet and LTE

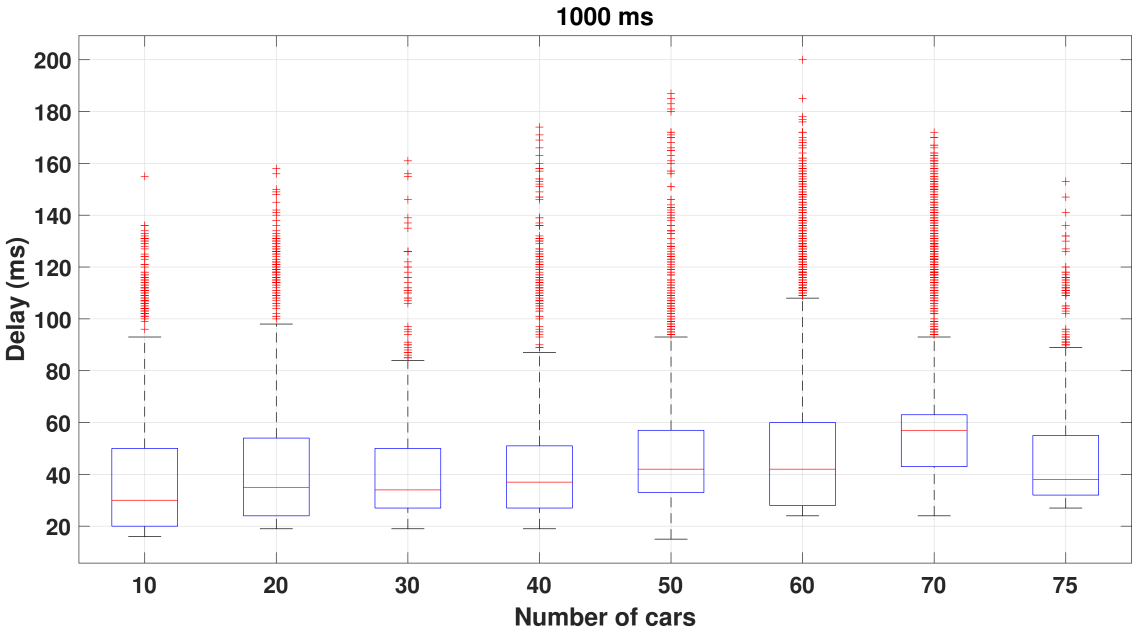

Figure 5.13: 1000ms dissemination interval for Ethernet and LTE

Comparatively to the ITS-G5 case, the delay values are far more distributed along the time axis (the *outliers* are uniformly placed from the upper *whisker* up to 200ms). This difference can be explained by the amount of traffic being exchanged from the laboratory and the internet and even by the different routes that each packet could do through the internet from the RSU to the broker and from the broker to the OBU. On the other hand, similar to ITS-G5 the number of bytes increased the average delay of the packets (this fact was only not observed in the 400ms, with the simulation of 30 vehicles).

LTE to LTE

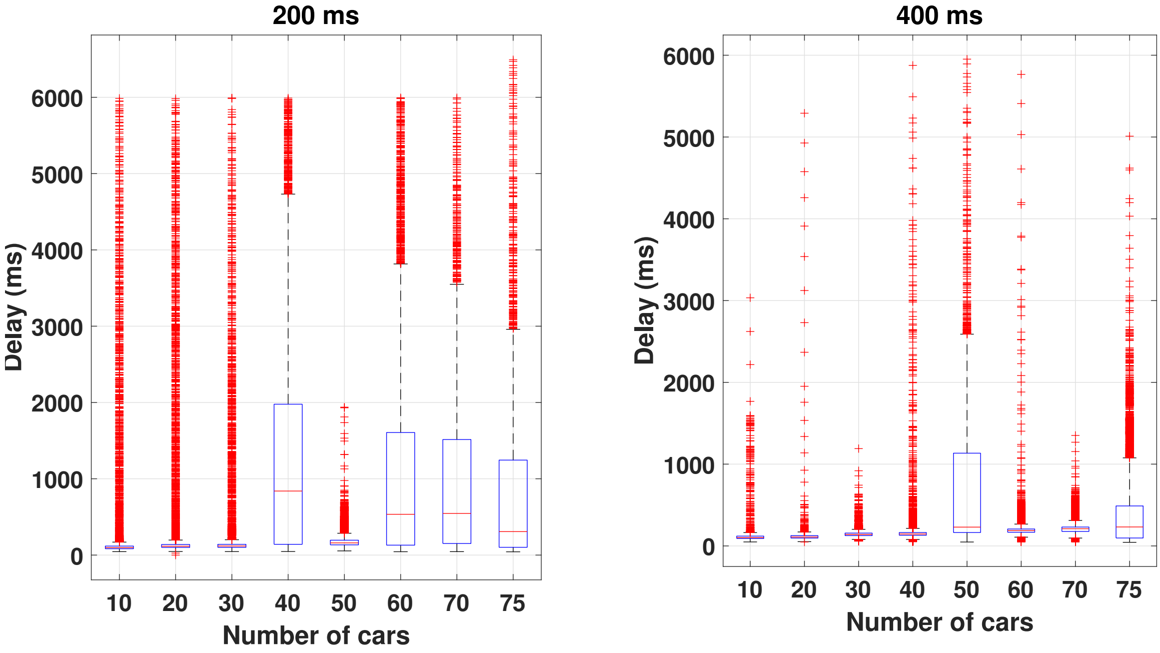

Figure 5.14: 200ms and 400ms dissemination intervals when both ITS-Ss use LTE

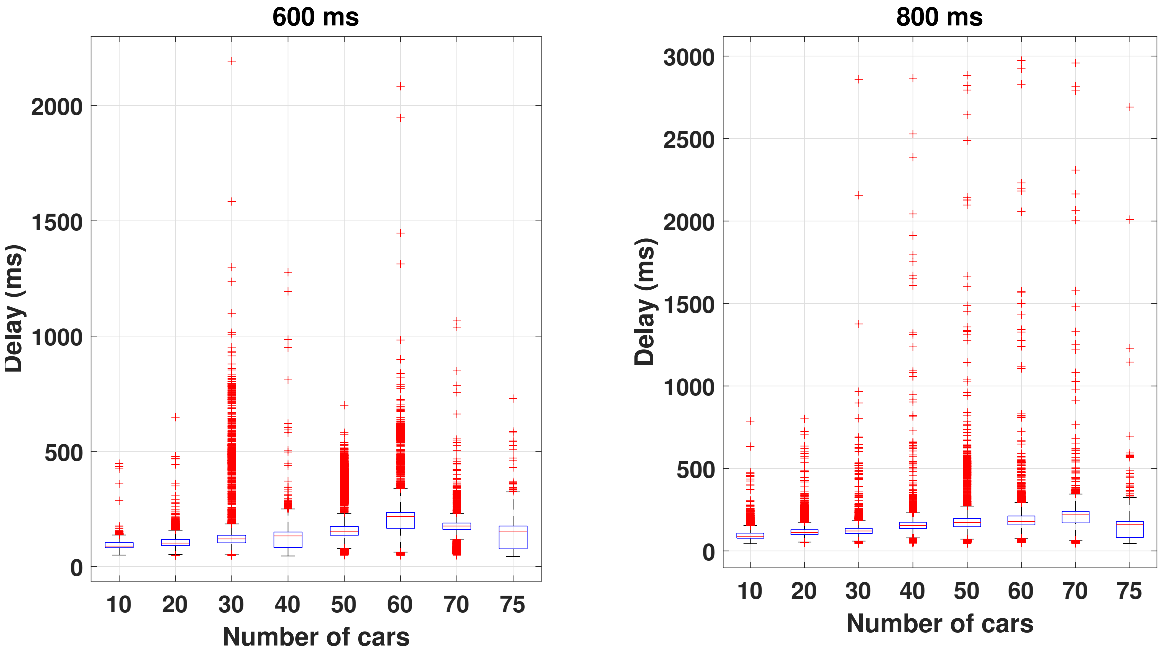

Figure 5.15: 600ms and 800ms dissemination intervals when both ITS-Ss use LTE

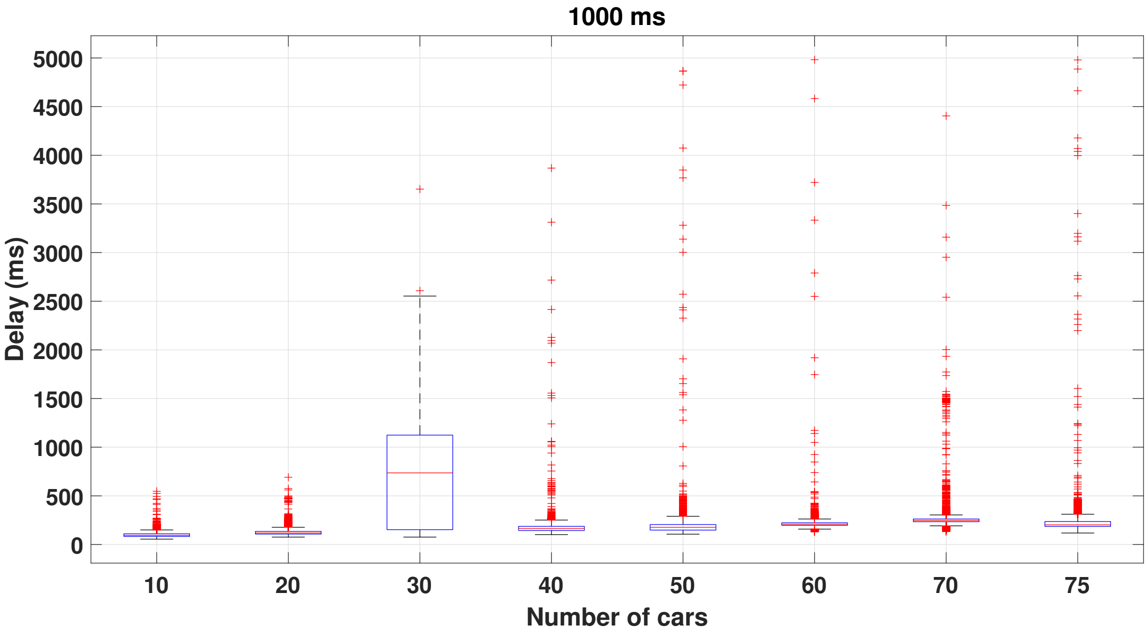

Figure 5.16: 1000ms dissemination interval when both ITS-Ss use LTE

Despite the average values being close to the 100 ms mark, the number of *outliers* shows that this solution presents too much fluctuation in the delay measurements. In general it is possible to see that when the number of cars is greater, the average delay value also grows. These results show that when both ITS-Ss use cellular communications, it is difficult to achieve reliable dissemination of safety-critical messages even in low traffic density situations.

5.4 RESULTS DISCUSSION

As mentioned in the beginning of the chapter, the performed tests intend to assess if the CPS respects the delay boundaries required to be implemented in road safety use cases and if it scales well for more demanding scenarios. The obtained results showed that the CPS overall dissemination delay respects the initial 100 ms imposed by the road safety applications defined in the BSA. The inter-layer delays measured, showed to have a low contribution to the total delay of the message dissemination chain. This fact did not changed even when the maximum SDU size is achieved. It is worth to mention that the tests measured the longest path that the CPM has to traverse before being disseminated through the ITS-G5, since when communicating via MQTT it only pass through the applications service. Regardless, the maximum value registered is below (by a safe margin) the 50 ms imposed by the ETSI CAM standard.

The dynamic generation rules have also proven to be an important feature in regulating the traffic data, producing almost 40% less bytes in the 200 ms dissemination interval. The results obtained also represent a worst case scenario (figure 5.2), since all the vehicles simulated maintain a constant velocity (approximately 10 m/s). This means that the scenarios simulated are closer to a high dense and dynamic environment rather than a congested scenario (more typical for a high number of vehicles). Nevertheless, the dynamic rules present an improvement in channel efficiency when a high number of vehicles is simulated, which is the most likely scenario for the radio channel to be congested if the penetration rate of connected vehicles is high. On the other hand, in a low density scenario, the improvement obtained by the dynamic rules activation is not so relevant since the number of vehicles does not justify the use of these rules. The trigger for the transition between static rules and dynamic rules could be obtained by the DCC mechanism, to balance between perception and channel efficiency.

For the end-to-end transmission delay between platforms, the constraint value of **100 ms** is achievable by the ITS-G5 radio technology. The worst result of **50 ms** (measured once) show that the content deliver by the CPMs is relevant for the safety-critical applications of the road environment giving a safe margin for communication issues such as multipath and non-direct LOS. On the other hand the delay constraint cannot be assured via broker dissemination. The Ethernet to LTE test showed that even with average values below 100 ms, the safe margin is not achievable since there are measurements reaching the 200 ms. Although the delay depends on different factors such as the number of users connected to a base station, LOS or the amount of traffic exchanged, the values measured would still have an great amount of delay, not suitable for safety-critical applications. The scenario when the RSU uses LTE to reach the MQTT broker demonstrates this issue clearly. Despite not being targeted for safety-critical applications, cellular communication dissemination, could be suitable to provide reasonable up-to-date information from the RSU to the vehicles using the adjacent topic subscription feature implemented in the OBUs.

CHAPTER 6

Conclusion and Future Work

The connected road infrastructure can provide to the C-ITS environment valuable information due to their advantageous position and resource availability. Although CAM provide important information for connected vehicles localization, the gradual penetration rate of ITS services require disseminated information to include all the road participants (including the road objects and non-connected vehicles) in order to assure the best reliability possible in road safety applications. The work developed in this dissertation focused on implementing the Collective Perception Service standardized by ETSI in a real road infrastructure and output the information to the user. Using the available resources and the already deployed infrastructure from PASMO's project, it was possible to retrieve data captured by a traffic radar and successfully disseminate CPMs in the local area using short-range communications through ITS-G5, and to a cloud MQTT broker by making use of radio link, optical fiber and LTE connections. This will help connected vehicles to extend their local perception system features by making use of cooperative information. Moreover, as shown through the results from the tests performed, the use of dynamic generation rules improve overall channel efficiency by controlling the amount of data disseminated in more congested environments without compromising the overall system performance. With relative low time delays, the service fulfills road safety applications requirements by respecting the maximum time delay imposed by ETSI in the BSA.

Regarding the future work, some aspects could be improved regarding the CP performance and the radio efficiency and costs. Support for other sensors such as LiDAR or cameras can improve the overall usability of the CPS on the RSUs, and give to possibility to migrate it to the OBU for CPMs dissemination. This aspect could lead to another feature that is the use of sensor fusion algorithms to reduce uncertainties in the objects parameters included in the CPMs and help filling all the optional information creating a more complete and robust message. This could include object classification, confidence and free space calculation that, in turn, will unlock the possibility of including more frequency management rules to improve channel efficiency. Another step forward for the CPS is to include an object dropped in a current CPM (due to maximum SDU size achieved, or dropped by the DCC) in the next generated CPM (CPM segmentation). This mechanism is in compliance with the ETSI standard, and therefore brings value to the work done. The integration of the MCS can also be seen as a future implementation work since highly relies on the CPM content for AV maneuvering and coordination. As for improving the delay from the MQTT broker path, pushing this cloud service close to the edge (road infrastructure) could be seen as an important step even to support safety-critical applications.

Regarding radio costs, another possible improvement is the implementation of a detection mechanism that when in an RSU's range, the OBU message dissemination should be exclusive to the ITS-G5, leaving the broker publishing message for the RSU. This will exclude the costs of data transfer using the OBU's LTE connection and duplicate message publication.

Bibliography

[1] European Automobile Manufacturers Association, "Vehicles in use Europe 2019", ACEA, European Union, Tech. Rep., 2019, p. 20. [Online]. Available: `https://www.acea.be/uploads/publications/ACEA_Report_Vehicles_in_use-Europe_2019.pdf`.

[2] Eurostat, "Freight transport statistics-modal", European Union, Tech. Rep., 2020, p. 11. [Online]. Available: `https://ec.europa.eu/eurostat/statistics-explained/index.php?title=Freight_transport_statistics_-_modal_split`.

[3] European Automobile Manufacturers Association, "The Automobile Industry Pocket Guide", ACEA, Tech. Rep., 2020, p. 88. [Online]. Available: `https://www.acea.be/uploads/publications/ACEA_Pocket_Guide_2020-2021.pdf`.

[4] Eurostat, "Transport statistics at regional level", European Union, Tech. Rep., 2020, p. 17. [Online]. Available: `https://ec.europa.eu/eurostat/statistics-explained/index.php?title=Transport_statistics_at_regional_level#Road_transport_and_accidents`.

[5] W. H. Organization, "Global status report on road safety", World Health Organization, Tech. Rep., 2018, p. 403. [Online]. Available: `https://apps.who.int/iris/bitstream/handle/10665/276462/9789241565684-eng.pdf`.

[6] A. Christodoulou, P. Christidis, and J. R. Centre, "Measuring congestion in European cities", Tech. Rep., 2020, p. 31. [Online]. Available: `https://op.europa.eu/en/publication-detail/-/publication/e590d815-9b08-11ea-9d2d-01aa75ed71a1/language-en/format-PDF/source-178542437`.

[7] A. Kaźmierczak, A. E. Envirnment, Mitigation, E. T. C. f. A. P. Change, and Climate, "Unequal exposure and unequal impacts: social vulnerability to air pollution, noise and extreme temperatures in Europe", Tech. Rep., 2019, p. 97. DOI: `10.2800/324183`. [Online]. Available: `https://www.eea.europa.eu/publications/unequal-exposure-and-unequal-impacts`.

[8] E. Comission, "A European strategy on Cooperative Intelligent Transport Systems, a milestone towards cooperative, connected and automated mobility", 2016. [Online]. Available: `https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX%3A52016DC0766`.

[9] ——, "Standardisation Mandate Addressed to CEN, CENELEC And ETSI in the field of information and communication technologies to support the interoperability of Co-operative systems for Intelligent Transport in the European Community", 2009. [Online]. Available: `https://ec.europa.eu/growth/tools-databases/mandates/index.cfm?fuseaction=search.detail&id=434#`.

[10] ETSI, "Intelligent Transport Systems", Tech. Rep., 2018. [Online]. Available: `https://www.etsi.org/images/files/ETSITechnologyLeaflets/IntelligentTransportSystems.pdf`.

[11] R. Bossom, R. Brignolo, T. Ernest, K. Evensen, A. Frötscher, W. Höfs, J. Jääskeläinen, Z. Jeftic, P. Kompfner, T. Kosch, I. Kulp, A. Kung, A.-K. Mokaddem, A. Schalk, E. Uhlemann, and C. Wewetzer, "D31 European ITS Communication Architecture Overall Framework Proof of Concept Implementation", Tech. Rep., 2009, p. 165.

[12] ETSI, "EN 302 665 - V1.1.1 - Intelligent Transport Systems (ITS); Communications Architecture", Tech. Rep., 2010, p. 44.

[13] T. Kosch, I. Kulp, M. Bechler, M. Strassberger, B. Weyl, and R. Lasowski, "Communication architecture for cooperative systems in Europe", *IEEE Communications Magazine*, vol. 47, no. 5, pp. 116–125, 2009, ISSN: 1558-1896. DOI: `10.1109/MCOM.2009.4939287`.

[14] ETSI, “EN 302 636-3 - V1.2.1 - Intelligent Transport Systems (ITS); Vehicular Communications; GeoNetworking; Part 3: Network Architecture”, Tech. Rep., 2014.

[15] ——, “Intelligent Transport Systems (ITS); Vehicular Communications; Basic Set of Applications; Definitions”, Tech. Rep., 2009.

[16] G. Karagiannis, O. Altintas, E. Ekici, G. Heijenk, B. Jarupan, K. Lin, and T. Weil, “Vehicular Networking: A Survey and Tutorial on Requirements, Architectures, Challenges, Standards and Solutions”, *IEEE Communications Surveys Tutorials*, vol. 13, no. 4, pp. 584–616, 2011, ISSN: 1553-877X. DOI: `10.1109/SURV.2011.061411.00019`.

[17] ETSI, “TS 102 637-1 - V1.1.1 - Intelligent Transport Systems (ITS); Vehicular Communications; Basic Set of Applications; Part 1: Functional Requirements”, Tech. Rep., 2010.

[18] ——, “Intelligent Transport Systems (ITS); Vehicular Communications; Basic Set of Applications; Definitions”, Tech. Rep., 2009.

[19] ——, “EN 302 636-5-1 - V2.1.0 - Intelligent Transport Systems (ITS); Vehicular Communications; GeoNetworking; Part 5: Transport Protocols; Sub-part 1: Basic Transport Protocol”, Tech. Rep., 2017.

[20] ——, “EN 302 637-2 - V1.4.1 - Intelligent Transport Systems (ITS); Vehicular Communications; Basic Set of Applications; Part 2: Specification of Cooperative Awareness Basic Service”, Tech. Rep., 2019.

[21] ——, “EN 302 637-3 - V1.2.1 - Intelligent Transport Systems (ITS); Vehicular Communications; Basic Set of Applications; Part 3: Specifications of Decentralized Environmental Notification Basic Service”, Tech. Rep., 2014.

[22] M. Alam, B. Fernandes, L. Silva, A. Khan, and J. Ferreira, “Implementation and analysis of traffic safety protocols based on ETSI Standard”, in *2015 IEEE Vehicular Networking Conference (VNC)*, 2015, pp. 143–150. DOI: `10.1109/VNC.2015.7385561`.

[23] ETSI, “TS 103 301 - V1.2.1 - Intelligent Transport Systems (ITS); Vehicular Communications; Basic Set of Applications; Facilities layer protocols and communication requirements for infrastructure services”, Tech. Rep., 2018.

[24] C-Roads, “C-ITS Infrastructure Functions and Specifications”, Tech. Rep., 2019.

[25] K. Garlichs, H. Günther, and L. C. Wolf, “Generation Rules for the Collective Perception Service”, in *2019 IEEE Vehicular Networking Conference (VNC)*, 2019, pp. 1–8. DOI: `10.1109/VNC48660.2019.9062827`.

[26] G. Thandavarayan, M. Sepulcre, and J. Gozalvez, “Analysis of Message Generation Rules for Collective Perception in Connected and Automated Driving”, in *2019 IEEE Intelligent Vehicles Symposium (IV)*, 2019, pp. 134–139. DOI: `10.1109/IVS.2019.8813806`.

[27] ETSI, “TR 103 562 - V2.1.1 - Intelligent Transport Systems (ITS); Vehicular Communications; Basic Set of Applications; Analysis of the Collective Perception Service (CPS); Release 2”, Tech. Rep., 2019.

[28] H. Günther, R. Riebl, L. Wolf, and C. Facchi, “Collective perception and decentralized congestion control in vehicular ad-hoc networks”, in *2016 IEEE Vehicular Networking Conference (VNC)*, 2016, pp. 1–8. DOI: `10.1109/VNC.2016.7835931`.

[29] ETSI, *Intelligent Transport Systems (ITS); Vehicular Communications; Basic Set of Applications; Maneuver Coordination Service.* (visited on 01/06/2021).

[30] ——, *Intelligent Transport Systems (ITS); Vehicular Communications; Informative report for the Maneuver Coordination Service.* (visited on 01/06/2021).

[31] J. Hodgkiss, S. Djahel, and Y. Hadjadj-Aoul, “An Advanced Coordination Protocol for Safer and more Efficient Lane Change for Connected and Autonomous Vehicles”, in *2019 16th IEEE Annual Consumer Communications Networking Conference (CCNC)*, Jan. 2019, pp. 1–4. DOI: `10.1109/CCNC.2019.8651668`.

[32] F. Michaud, P. Lepage, P. Frenette, D. Letourneau, and N. Gaubert, “Coordinated Maneuvering of Automated Vehicles in Platoons”, *IEEE Transactions on Intelligent Transportation Systems*, vol. 7, no. 4, pp. 437–447, 2006, ISSN: 1558-0016. DOI: `10.1109/TITS.2006.883939`.

[33] L. Sequeira, A. Szefer, J. Slome, and T. Mahmoodi, “A Lane Merge Coordination Model for a V2X Scenario”, in *2019 European Conference on Networks and Communications (EuCNC)*, 2019, pp. 198–203. DOI: `10.1109/EuCNC.2019.8801987`.

[34] B. Lehmann, H. Günther, and L. Wolf, “A Generic Approach towards Maneuver Coordination for Automated Vehicles”, in *2018 21st International Conference on Intelligent Transportation Systems (ITSC)*, Nov. 2018, pp. 3333–3339. DOI: `10.1109/ITSC.2018.8569442`.

[35] W. Xu, A. Willecke, M. Wegner, L. Wolf, and R. Kapitza, “Autonomous Maneuver Coordination Via Vehicular Communication”, in *2019 49th Annual IEEE/IFIP International Conference on Dependable Systems and Networks Workshops (DSN-W)*, 2019, pp. 70–77. DOI: `10.1109/DSN-W.2019.00022`.

[36] A. Correa, R. Alms, J. Gozalvez, M. Sepulcre, M. Rondinone, R. Blokpoel, L. Lücken, and G. Thandavarayan, “Infrastructure Support for Cooperative Maneuvers in Connected and Automated Driving”, in *2019 IEEE Intelligent Vehicles Symposium (IV)*, 2019, pp. 20–25. DOI: `10.1109/IVS.2019.8814044`.

[37] T. Kosch, C. J. Adler, S. Eichler, C. Schroth, and M. Strassberger, “The scalability problem of vehicular ad hoc networks and how to solve it”, *IEEE Wireless Communications*, vol. 13, no. 5, pp. 22–28, 2006, ISSN: 1558-0687. DOI: `10.1109/WC-M.2006.250354`.

[38] M. Lee and T. Atkison, “VANET applications: Past, present, and future”, *Vehicular Communications*, vol. 28, p. 100 310, 2021, ISSN: 2214-2096. DOI: `https://doi.org/10.1016/j.vehcom.2020.100310`.

[39] R. Kaur, T. P. Singh, and V. Khajuria, “Security Issues in Vehicular Ad-Hoc Network(VANET)”, in *2018 2nd International Conference on Trends in Electronics and Informatics (ICOEI)*, 2018, pp. 884–889. DOI: `10.1109/ICOEI.2018.8553852`.

[40] E. C. o. P. Administrations and Telecommunications, “Report from CEPT to EC in response to the Mandate on “the harmonised radio spectrum use for safety critical applications of Intelligent Transport Systems (ITS) in the European Union””, Tech. Rep., 2007. [Online]. Available: `https://docdb.cept.org/document/20`.

[41] ETSI, “EN 302 571 - V2.1.1 - Intelligent Transport Systems (ITS); Radiocommunications equipment operating in the 5 855 MHz to 5 925 MHz frequency band; Harmonised Standard covering the essential requirements of article 3.2 of Directive 2014/53/EU”, Tech. Rep., 2017.

[42] E. Comission, “2008/671/EC: Commission Decision of 5 August 2008 on the harmonised use of radio spectrum in the 5875 - 5905 MHz frequency band for safety-related applications of Intelligent Transport Systems (ITS) (notified under document number C(2008) 4145)”, 2008. [Online]. Available: `https://eur-lex.europa.eu/eli/dec/2008/671/oj`.

[43] ETSI, “EN 302 663 - V1.3.1 - Intelligent Transport Systems (ITS); ITS-G5 Access layer specification for Intelligent Transport Systems operating in the 5 GHz frequency band”, Tech. Rep., 2019.

[44] ——, “TS 102 724 - V1.1.1 - Intelligent Transport Systems (ITS); Harmonized Channel Specifications for Intelligent Transport Systems operating in the 5 GHz frequency band”, Tech. Rep., 2012.

[45] ——, “EN 301 893 - V2.0.7 - 5 GHz RLAN; Harmonised Standard covering the essential requirements of article 3.2 of Directive 2014/53/EU”, Tech. Rep., 2016.

[46] ——, “EN 302 663 - V1.2.1 - Intelligent Transport Systems (ITS); Access layer specification for Intelligent Transport Systems operating in the 5 GHz frequency band”, Tech. Rep., 2013.

[47] S. Gopinath, L. Wischhof, C. Ponikwar, and H. Hof, “Hybrid solutions for data dissemination in vehicular networks”, in *2016 Wireless Days (WD)*, 2016, pp. 1–4. DOI: `10.1109/WD.2016.7461519`.

[48] IEEE, “IEEE Standard for Information technology—Telecommunications and information exchange between systems Local and metropolitan area networks—Specific requirements - Part 11: Wireless LAN Medium Access Control (MAC) and Physical Layer (PHY) Specifications”, *IEEE Std 802.11-2016 (Revision of IEEE Std 802.11-2012)*, pp. 1–3534, 2016. DOI: `10.1109/IEEESTD.2016.7786995`.

[49] ETSI, “TS 102 687 - V1.2.1 - Intelligent Transport Systems (ITS); Decentralized Congestion Control Mechanisms for Intelligent Transport Systems operating in the 5 GHz range; Access layer part”, Tech. Rep., 2018.

[50] IEEE, "IEEE Standard for Information technology– Local and metropolitan area networks– Specific requirements– Part 11: Wireless LAN Medium Access Control (MAC) and Physical Layer (PHY) Specifications Amendment 6: Wireless Access in Vehicular Environments", *IEEE Std 802.11p-2010 (Amendment to IEEE Std 802.11-2007 as amended by IEEE Std 802.11k-2008, IEEE Std 802.11r-2008, IEEE Std 802.11y-2008, IEEE Std 802.11n-2009, and IEEE Std 802.11w-2009)*, pp. 1–51, 2010. DOI: `10.1109/IEEESTD.2010.5514475`.

[51] ——, "IEEE Standard for Information Technology - Telecommunications and Information Exchange Between Systems - Local and Metropolitan Area Networks - Specific Requirements - Part 11: Wireless LAN Medium Access Control (MAC) and Physical Layer (PHY) Specificatio", *IEEE Std 802.11-2007 (Revision of IEEE Std 802.11-1999)*, pp. 1–1076, 2007. DOI: `10.1109/IEEESTD.2007.373646`.

[52] F. Arena, G. Pau, and A. Severino, "A Review on IEEE 802.11p for Intelligent Transportation Systems", *Journal of Sensor and Actuator Networks*, vol. 9, no. 2, 2020, ISSN: 2224-2708. DOI: `10.3390/jsan9020022`.

[53] D. Jiang and L. Delgrossi, "IEEE 802.11p: Towards an International Standard for Wireless Access in Vehicular Environments", in *VTC Spring 2008 - IEEE Vehicular Technology Conference*, 2008, pp. 2036–2040. DOI: `10.1109/VETECS.2008.458`.

[54] IEEE, "IEEE Standard for Telecommunications and Information Exchange Between Systems - LAN/MAN Specific Requirements - Part 11: Wireless Medium Access Control (MAC) and physical layer (PHY) specifications: High Speed Physical Layer in the 5 GHz band", *IEEE Std 802.11a-1999*, pp. 1–102, 1999. DOI: `10.1109/IEEESTD.1999.90606`.

[55] ——, "IEEE Standard for Information technology–Local and metropolitan area networks–Specific requirements–Part 11: Wireless LAN Medium Access Control (MAC) and Physical Layer (PHY) Specifications - Amendment 8: Medium Access Control (MAC) Quality of Service", *IEEE Std 802.11e-2005 (Amendment to IEEE Std 802.11, 1999 Edition (Reaff 2003)*, pp. 1–212, 2005. DOI: `10.1109/IEEESTD.2005.97890`.

[56] J. Almeida, J. Ferreira, and A. Oliveira, "Development of an ITS-G5 station, from the physical to the MAC layer", in *Intelligent Transportation Systems From Good Practices to Standards*, 2016, ISBN: 978-1-4987-2186-8. [Online]. Available: `http://hdl.handle.net/10773/21887`.

[57] B. Y. Yacheur, T. Ahmed, and M. Mosbah, "Analysis and comparison of ieee 802.11p and ieee 802.11bd", F. Krief, H. Aniss, L. Mendiboure, S. Chaumette, and M. Berbineau, Eds., pp. 55–65, 2020.

[58] J. Wannstrom, *High Speed Packet data Access.* [Online]. Available: `https://www.3gpp.org/technologies/keywords-acronyms/99-hspa` (visited on 04/05/2021).

[59] 3GPP, "Feasibility study for evolved Universal Terrestrial Radio Access (UTRA) and Universal Terrestrial Radio Access Network (UTRAN)", 3rd Generation Partnership Project (3GPP), TR 25.912, 2007. [Online]. Available: `http://www.3gpp.org/ftp/Specs/html-info/25912.htm`.

[60] ——, "Requirements for Evolved UTRA (E-UTRA) and Evolved UTRAN (E-UTRAN)", 3rd Generation Partnership Project (3GPP), TR 25.913, 2006. [Online]. Available: `http://www.3gpp.org/ftp/Specs/html-info/25913.htm`.

[61] ETSI, *4G - Long Term Evolution | LTE Standards.* [Online]. Available: `https://www.etsi.org/technologies/mobile/4G` (visited on 04/05/2021).

[62] C. Cox, *An Introduction to LTE: LTE, LTE-Advanced, SAE, VoLTE and 4G Mobile Communications.* Chennai: John Wiley Sons Ltd, 2014, p. 488. [Online]. Available: `https://ieeexplore.ieee.org/servlet/opac?bknumber=8039851`.

[63] A. Ghosh, J. Zhang, J. G. Andrews, and R. Muhamed, *Fundamentals of LTE*, 1st. USA: Prentice Hall Press, 2010, ISBN: 0137033117. [Online]. Available: `https://dl.acm.org/doi/book/10.5555/1941366`.

[64] M. Nohrborg, *LTE Overview.* [Online]. Available: `https://www.3gpp.org/technologies/keywords-acronyms/98-lte` (visited on 04/05/2021).

[65] ITU-R, *Invitation for submission of proposals for candidate radio interface technologies for the terrestrial components of the radio interface(s) for IMT-Advanced and invitation to participate in their subsequent*

evaluation, 2008. [Online]. Available: `https://www.itu.int/md/R00-SG05-CIR-0002/en` (visited on 04/05/2021).

[66] 3GPP, "Feasibility study for Further Advancements for E-UTRA (LTE-Advanced)", 3rd Generation Partnership Project (3GPP), TR 36.912, 2009. [Online]. Available: `http://www.3gpp.org/ftp/Specs/html-info/36912.htm`.

[67] ——, "Requirements for further advancements for E-UTRA (LTE-Advanced)", 3rd Generation Partnership Project (3GPP), TR 36.913, 2008. [Online]. Available: `http://www.3gpp.org/ftp/Specs/html-info/36913.htm`.

[68] H. Holma and A. Toskala, *LTE Advanced: 3GPP Solution for IMT-Advanced.* John Wiley Sons Ltd, 2012, p. 248. [Online]. Available: `https://ieeexplore.ieee.org/servlet/opac?bknumber=8039772`.

[69] 3GPP, *ITU-R Confers IMT-Advanced (4G) Status to 3GPP LTE*, 2010. [Online]. Available: `https://www.3gpp.org/news-events/1319-ITU-R-Confers-IMT-Advanced-4G-Status-to-3GPP-LTE` (visited on 04/05/2021).

[70] E. Dahlman, S. Parkvall, and J. Skold, *4G, LTE-Advanced Pro and The Road to 5G.* Academic Press, 2016, p. 616. [Online]. Available: `https://www.sciencedirect.com/book/9780128045756/4g-lte-advanced-pro-and-the-road-to-5g`.

[71] 5GAA, *Coexistence of C-V2X and 802.11p at 5.9 GHz – 5G Automotive Association*, 2017. [Online]. Available: `https://5gaa.org/news/position-paper-coexistence-of-c-v2x-and-802-11p-at-5-9-ghz/` (visited on 04/05/2021).

[72] ——, *An assessment of LTE-V2X (PC5) and 802.11p direct communications technologies for improved road safety in the EU*, 2017. [Online]. Available: `https://5gaa.org/news/an-assessment-of-lte-v2x-pc5-and-802-11p-direct-communications-technologies-for-improved-road-safety-in-the-eu/` (visited on 04/05/2021).

[73] M. Sauter, *From GSM to LTE-Advanced Pro and 5G.* John Wiley Sons Ltd, 2017, p. 544. [Online]. Available: `https://onlinelibrary.wiley.com/doi/abs/10.1002/9781119346913.fmatter`.

[74] 3GPP, "Release description; Release 15", 3rd Generation Partnership Project (3GPP), TR 21.915, 2018. [Online]. Available: `http://www.3gpp.org/ftp/Specs/html-info/21915.htm`.

[75] ITU-R, *Invitation for submission of proposals for candidate radio interface technologies for the terrestrial components of the radio interface(s) for IMT-2020 and invitation to participate in their subsequent evaluation.* [Online]. Available: `https://www.itu.int/md/R00-SG05-CIR-0059/en` (visited on 04/05/2021).

[76] 3GPP, "Release description; Release 16", 3rd Generation Partnership Project (3GPP), TR 21.916, 2019. [Online]. Available: `http://www.3gpp.org/ftp/Specs/html-info/21916.htm`.

[77] Y. Wang, G. de Veciana, T. Shimizu, and H. Lu, "Performance and Scaling of Collaborative Sensing and Networking for Automated Driving Applications", in *2018 IEEE International Conference on Communications Workshops (ICC Workshops)*, 2018, pp. 1–6. DOI: `10.1109/ICCW.2018.8403778`.

[78] G. Thandavarayan, M. Sepulcre, and J. Gozalvez, "Analysis of Message Generation Rules for Collective Perception in Connected and Automated Driving", in *2019 IEEE Intelligent Vehicles Symposium (IV)*, 2019, pp. 134–139. DOI: `10.1109/IVS.2019.8813806`.

[79] G. Thandavarayan, M. Sepulcre, and J. Gozalvez, "Generation of Cooperative Perception Messages for Connected and Automated Vehicles", *IEEE Transactions on Vehicular Technology*, vol. 69, no. 12, pp. 16 336–16 341, 2020, ISSN: 1939-9359. DOI: `10.1109/TVT.2020.3036165`.

[80] A. Chtourou, P. Merdrignac, and O. Shagdar, "Collective Perception service for Connected Vehicles and Roadside Infrastructure", in *2021 IEEE 93rd Vehicular Technology Conference (VTC2021-Spring)*, 2021, pp. 1–5. DOI: `10.1109/VTC2021-Spring51267.2021.9448753`.

[81] H. Guo, J. Liu, J. Ren, and Y. Zhang, "Intelligent task offloading in vehicular edge computing networks", *IEEE Wireless Communications*, vol. 27, no. 4, pp. 126–132, 2020, ISSN: 1558-0687. DOI: `10.1109/MWC.001.1900489`.

[82] H. El-Sayed and M. Chaqfeh, "Exploiting Mobile Edge Computing for Enhancing Vehicular Applications in Smart Cities", *Sensors*, vol. 19, no. 5, 2019, ISSN: 1424-8220. DOI: `10.3390/s19051073`.

[83] *Perception Augmentée par coopération V2X*. [Online]. Available: `http://pacv2x.fr` (visited on 09/06/2021).

[84] P. Merdrignac, O. Shagdar, S. Tohmé, and J.-L. Franchineau, "Augmented Perception by V2X Communication for Safety of Autonomous and Non-Autonomous Vehicles", Apr. 2018. DOI: `10.5281/ZENODO.1483385`.

[85] A. Jandial, P. Merdrignac, O. Shagdar, and L. Fevrier, "Implementation and Evaluation of Intelligent Roadside Infrastructure for Automated Vehicle with I2V Communication", in *Vehicular Ad-hoc Networks for Smart Cities*, A. Laouiti, A. Qayyum, and M. N. Mohamad Saad, Eds., Singapore: Springer Singapore, 2020, pp. 3–18, ISBN: 978-981-15-3750-9.

[86] M. Shan, K. Narula, Y. F. Wong, S. Worrall, M. Khan, P. Alexander, and E. Nebot, "Demonstrations of Cooperative Perception: Safety and Robustness in Connected and Automated Vehicle Operations", *Sensors*, vol. 21, no. 1, 2021, ISSN: 1424-8220. DOI: `10.3390/s21010200`.

[87] A. Dosovitskiy, G. Ros, F. Codevilla, A. Lopez, and V. Koltun, "CARLA: An open urban driving simulator", in *Proceedings of the 1st Annual Conference on Robot Learning*, 2017, pp. 1–16.

[88] *Managing Automated Vehicles Enhances Network*. [Online]. Available: `http://www.maven-its.eu/` (visited on 09/06/2021).

[89] *Intelligent Maneuver Automation – cooperative hazard avoidance in realtime*. [Online]. Available: `https://www.imagine-online.de/home` (visited on 09/06/2021).

[90] *Transition Areas for Infrastructure-Assisted Driving*. [Online]. Available: `https://www.transaid.eu/` (visited on 09/06/2021).

[91] J. Schindler, B. Coll-Perales, X. Zhang, M. Rondinone, and G. Thandavarayan, "Infrastructure-supported cooperative automated driving in transition areas", in *2020 IEEE Vehicular Networking Conference (VNC)*, 2020, pp. 1–8. DOI: `10.1109/VNC51378.2020.9318392`.

[92] *AtoBe, Mobility Technology, SA*. [Online]. Available: `https://www.a-to-be.com/about-us/` (visited on 09/06/2021).

[93] *C-Roads*. [Online]. Available: `https://www.c-roads.eu/platform.html` (visited on 09/06/2021).

[94] J. Almeida, E. Vieira, J. Ferreira, J. Ribeiro, T. Dias, and L. Moura, "Roadside and Cloud Architecture for C-ITS Services", in *27th ITS World Congress, Hamburg, Germany, 11-15 October*, 2021.

[95] O. Dubuisson, *ASN.1 Communication between Heterogeneous Systems*. 2000, p. 562, ISBN: 0126333610.

[96] "ITU-T Information technology-Abstract Syntax Notation One (ASN.1): Specification of basic notation", 2002.

[97] *Mosquitto: MQ Telemetry Transport*. [Online]. Available: `https://mosquitto.org/man/mqtt-7.html` (visited on 09/06/2021).

[98] PC Engines, *Apu3 series system board*, 2016, p. 10.

[99] Compex Systems Pte. Ltd., *Full-size PCIe mini card WLE200NX*, 2010, p. 5.

[100] Atheros Communications, *AR9280 Single-chip 2.4/5 GHz 802.11n WLAN solution for PCI-express*, 2010, p. 2.

[101] Huawei Technologies, *ME909s-120 For M2M application, European market*, p. 2.

[102] ——, *HUAWEI ME909s Series LTE Mini PCIe Module, Hardware Guide*, 2016, p. 76.

[103] Smartmicro, *UMRR Traffic Management Sensor Type 42 Data Sheet*, 2020, p. 25.

[104] ——, *UMRR Traffic Management Sensor User Manual version 2*, 2017, p. 19.

[105] *About Arch Linux*. [Online]. Available: `https://archlinux.org/about/` (visited on 09/28/2021).

[106] *Central Regulatory Domain Agent.* [Online]. Available: `https://wireless.wiki.kernel.org/en/developers/regulatory/crda` (visited on 09/28/2021).

[107] *Wireless Regulatory Domain Implementation.* [Online]. Available: `https://wireless.wiki.kernel.org/en/developers/regulatory` (visited on 09/28/2021).

[108] *About iw.* [Online]. Available: `https://wireless.wiki.kernel.org/en/users/documentation/iw` (visited on 09/28/2021).

[109] *ip(8) — Linux manual page.* [Online]. Available: `https://man7.org/linux/man-pages/man8/ip.8.html` (visited on 09/28/2021).

[110] *Mobile Broadband Interface Model v1.0.* [Online]. Available: `https://www.usb.org/document-library/mobile-broadband-interface-model-v10-errata-1-and-adopters-agreement` (visited on 09/28/2021).

[111] *MBIM-NETWORK man page.* [Online]. Available: `https://www.freedesktop.org/software/libmbim/man/latest/mbim-network.1.html` (visited on 09/28/2021).

[112] *MBIMCLI man page.* [Online]. Available: `https://www.freedesktop.org/software/libmbim/man/latest/mbimcli.1.html` (visited on 09/28/2021).

[113] *PASMO, Open Platform for the development and experimentation of Solutions for Mobility.* [Online]. Available: `https://pasmo.pt/project/pasmo` (visited on 09/28/2021).

[114] "Ieee standard for a precision clock synchronization protocol for networked measurement and control systems", *IEEE Std 1588-2019 (Revision ofIEEE Std 1588-2008)*, pp. 1–499, 2020. DOI: `10.1109/IEEESTD.2020.9120376`.

[115] EndRun Technologies, *Precision Time Protocol (PTP/IEEE-1588)*, Santa Rosa,USA.

[116] ——, *Introduction to NTP*, Santa Rosa,USA.