POLITECNICO DI TORINO

Master's Degree in Mechatronic Engineering

Master's Degree Thesis

Implementation and experimental evaluation of a Local Dynamic Map for Road Data Aggregation with the support of vehicular micro-clouds

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Summary

The concept of autonomous driving in today worlds' transportation systems is of high importance. A lot of studies are investigating the challenges and opportunities related to the transportation policies that will arise as a result of emerging Autonomous Vehicle (AV) technologies.

In addition to Intelligent Transport Systems (ITS) applications that rely only on the sensor information of an ego vehicle, recent studies are also examining cooperative ITS paradigms on which the sensor information is shared through by the use of the vehicle-to-everything (V2X) communications. This information could be exchanged in the network based on standardized ITS messages, defined by the European Telecommunications Standards Institute (ETSI), more specifically Cooperative Awareness Message (CAM), Decentralized Environmental Notification Message (DENM) and Collective Perception Message (CPM). The ITS-G5 set of protocols support wide range of heterogeneous application requirements and enables Vehicle-2-Vehicle (V2V) and Vehicle-to-Infrastructure (V2I) communication in mobile environments.

One of the key facility elements in the co-operative ITS, is the Local Dynamic Map (LDM) that maintains the information about all the objects influencing or being part of the traffic, enabling ITS applications to retrieve it on demand. All the V2X-enabled vehicles have an LDM, which is a database filled with information from V2X messages such as CPMs and CAMs coming from nearby vehicles and the on-board sensors of the ego vehicle. The information found in CAMs are about the vehicles that are sending the message and the CPMs, instead, contain information about the vehicle's detected objects, found inside its LDM.

For a group of neighboring vehicles, because of the repetition of the gathered context information, there is the possibility to create a cluster, often referred to as vehicular micro-clouds, which enables the possibility to collectively process and aggregate the data. Platooning is one of the most popular V2X-enabled applications suitable for this architecture to be deployed in real life. Platoons are a cluster

of vehicles that manage to travel closely behind each other, in order to save fuel, reduce traffic and increase road safety.

The core of this work has been to evaluate the collective perception enhancement and the distribution of the computational load among the platoon members, to this end, we make use of MS-VAN3T, an open-source vehicular network simulation framework able to integrate multiple communication stacks such as IEEE 802.11p or LTE-V2X, built on the ns-3 simulator and the Simulation of the Urban Mobility (SUMO) to manage the mobility. In MS-VAN3T the message exchange is based on the standardized ITS messages defined by ETSI and It gives us the opportunity to model all aspects of communication among the various entities in a created vehicular scenario.

Acknowledgements

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Acronyms

ITS Intelligent Transportation Systems

VANET Vehicular Ad-Hoc Network

V2V Vehicle-to-Vehicle

V2I Vehicle-to-Infrastructure

V2X Vehicle-to-Everything

CA Cooperative Awareness

CAM Cooperative Awareness Message

DEN Decentralized Environmental Notification

DENM Decentralized Environmental Notification Message

CP Collective Perception

CPS Collective Perception Service

CPM Collective Perception Message

ETSI European Telecommunications Standards Institute

IEEE Institute of Electrical and Electronics Engineers

BTP Basic Transport Protocol

GN GeoNetworking

RSU Roadside Unit

OBU On Board Unit

3GPP 3rd Generation Partnership Project

DSRC Dedicated Short Range Communications

C-V2X Cellular Vehicle-to-Everything

LLC Logical Link Control

MAC Medium Access Control

WAVE Wireless Access in Vehicular Environments

ITS-S ITS Station

Chapter 1

Introduction

1.1 Intelligent Transport Systems

Since the early days of the automotive industry, manufacturers have been working to improve the safety of their vehicles. These efforts have resulted in the development and implementation of a wide range of safety features, including four-wheel hydraulic brakes, built-in seat belts, airbags, and many others. Before introducing these new features, car manufacturers conduct extensive research and testing to ensure that they are effective and safe for drivers and passengers. This often involves testing the new features in a variety of real-world conditions, as well as in laboratory settings. Manufacturers must also comply with government regulations and safety standards before introducing new safety features to their vehicles. Over time, many of these safety features have become standard in new cars, and consumers have come to expect them. As technology continues to evolve, car manufacturers will likely continue to develop and implement new safety features to make driving safer for everyone on the road.

In recent years, there has been a significant focus on Intelligent Transportation Systems (ITS) as a means of improving both the safety and efficiency of vehicles on the road. ITS encompasses a range of applications and services that use advanced technologies to improve the transportation experience for drivers and passengers. For example, systems that allow vehicles to communicate with each other and with the road infrastructure can help to prevent accidents and reduce congestion on the roads. Other applications, such as real-time traffic information and route planning, can help drivers to navigate more efficiently and avoid delays. Given the potential benefits of ITS, there has been a concerted effort by industry, government, and academic researchers to standardize the various aspects of these systems. This includes developing common technical standards, ensuring interoperability between different systems, and establishing protocols for data sharing and privacy.

Vehicular Ad-hoc Networks (VANETs) have played a critical role in enabling the ITS by providing a means for vehicles to communicate with each other and with the surrounding infrastructure. VANETs use Dedicated Short-Range Communication (DSRC) technology to allow the exchange of messages between vehicles and infrastructure in a fast and direct manner. This enables both Vehicle-to-Vehicle (V2V) and Vehicle-to-Infrastructure (V2I) communication, which is essential for many ITS applications. With V2V communication, vehicles can exchange information about their position, speed, and direction of travel, as well as information about road conditions, hazards, and other potential safety concerns. Similarly, with V2I communication, vehicles can communicate with the surrounding infrastructure to access real-time traffic information, receive traffic signal timing information, and obtain other useful data.

Collision avoidance is one of the most important ITS applications, and it involves the use of Cooperative Awareness Messages (CAMs) to exchange information between vehicles in order to avoid collisions. CAMs are standardized messages that contain information about the sending vehicle, such as its position, speed, acceleration, and heading. These messages are exchanged between vehicles using V2V communication, and they allow each vehicle to build a picture of the surrounding traffic and make autonomous decisions about how to proceed. By exchanging this information, vehicles can detect potential collision risks and take evasive action to avoid accidents. For example, if a vehicle detects that another vehicle is approaching too quickly or is on a collision course, it can take action to slow down or change lanes in order to avoid a collision. The standardization of CAMs by the European Telecommunications Standards Institute (ETSI) has helped to ensure interoperability between different ITS systems, allowing vehicles from different manufacturers and with different communication technologies to exchange information and work together to prevent accidents on the road [1].

While modern vehicles are equipped with increasingly sophisticated sensors and computing power, these capabilities are limited to the local view of the vehicle. To enable more effective collision avoidance applications, it is necessary to share information through VANETs with other vehicles and roadside units in order to provide a more comprehensive view of the driving environment. However, the effectiveness of these applications is highly dependent on the number of active players in the system, and the speed at which these technologies are adopted and become widespread. As the number of active vehicles and roadside units increases, the accuracy and reliability of the information exchanged also improves, leading to better performance of decision-making algorithms. This is why the concept of Penetration Rate, which refers to the percentage of vehicles equipped with V2V and V2I communication technologies, is so important. A higher Penetration Rate means that more vehicles are equipped with these technologies, leading to a more comprehensive view of the driving environment and more effective decision-making algorithms [2].

In addition to safety applications, traffic efficiency applications are another important area of research in the world of ITS. These applications aim to minimize the time it takes for a vehicle to travel from one point to another, while also reducing fuel consumption and pollutant emissions. One promising traffic efficiency application is the concept of Virtual Traffic Lights (VTL). In many cities, a low percentage of intersections are regulated by traffic lights, making them vulnerable to traffic loads and resulting in high inefficiencies. VTLs enable vehicles to exchange messages with each other to coordinate their movements and simulate a virtual traffic light that can be seen by drivers in their vehicle's built-in display. There are different approaches to implement VTLs, but one refined approach is to periodically select a vehicle to be the coordinator for each intersection. The coordinator broadcasts V2V messages with the traffic light signals, enabling a reduction in traffic congestion of up to 60 percent without the need for a coordinating infrastructure. This approach is especially effective at high vehicular densities. As with safety applications, the success of VTLs depends on the adoption of V2V and V2I communication technologies and the penetration rate of these technologies among vehicles on the road [3, 4].

Other applications that are used for traffic efficiency include Platooning and applications for Parking space search. Platooning is a concept that has been around for a while and involves grouping vehicles together in a way that allows them to behave as a single unit. Platooning has been studied as a way to reduce fuel consumption and emissions, particularly for Heavy Duty Vehicles (HDVs), which are more costly to operate than other vehicles due to their size and weight. By grouping HDVs together in a platoon and using V2V communication to maintain the platoon, air drag can be reduced, resulting in fuel savings and lower emissions [5]. As for parking space search applications, they can not only reduce the time and stress of finding a parking spot, but also reduce the amount of fuel wasted and emissions produced by vehicles circling around in search of a spot. This can be achieved through the use of sensors and cameras to detect the availability of parking spaces, as well as V2I communication to guide drivers to the nearest available spot. Some parking space search applications also make use of machine learning algorithms to predict parking availability based on historical data and events happening in the area [6].

In the field of ITS with so many different technologies and applications being developed, it's essential to have standardized protocols and frameworks to ensure interoperability and compatibility between systems. Several organizations, including the ETSI, the Institute of Electrical and Electronics Engineers (IEEE), and the 3rd Generation Partnership Project (3GPP), play crucial roles in developing and maintaining these standards. In the upcoming sections, a comparison of the different protocols and access technologies for connected vehicles is made with a special focus in the efforts made by ETSI in this regard.

1.2 VANETs

The Communication between vehicles, as explained, plays a significant role in the success of ITS applications. VANETs have been designed specifically to meet the unique requirements of vehicular communication. The key characteristics of VANETs that differentiate them from other ad-hoc networks, such as MANETs, are their ability to handle high mobility, support real-time and safety-critical applications, beside providing ultra low latency even with variable loads. These characteristics have made VANETs an essential component of ITS applications.

In order for communication to occur between vehicles and RSUs in a vehicular network, several hardware components are required. Vehicles need to be equipped with an On Board Unit (OBU), which is a device that provides wireless communication capabilities and enables short-range ad hoc networks to be formed with other OBUs and RSUs. In addition to OBUs, vehicles also require positioning hardware such as a GPS or DGPS receiver, which provides accurate location information. Fixed RSUs are also required in vehicular networks to facilitate communication between vehicles and the backbone network. RSUs are connected to the backbone network and act as gateways to the Internet or other external networks. The distribution of RSUs is a key factor in determining the effectiveness of the communication network, as it impacts the coverage area and the availability of communication services [7].

Vehicle-to-Everything (V2X) is a term used to describe the various communication configurations that can occur in a vehicular network. The four main configurations of V2X are:

- Vehicle-to-Vehicle (V2V)
- Vehicle-to-Infrastructure (V2I)
- Vehicle-to-Network (V2N)
- Vehicle-to-Pedestrian (V2P)

At present, vehicular networks are mainly based on two families of access technologies, namely Dedicated Short Range Communications (DSRC) and Cellular Vehicle-to-Everything (C-V2X).

- **Dedicated Short Range Communications (DSRC):** A short-range wireless communication technology based on IEEE 802.11p standards that is specifically designed for vehicular communications.

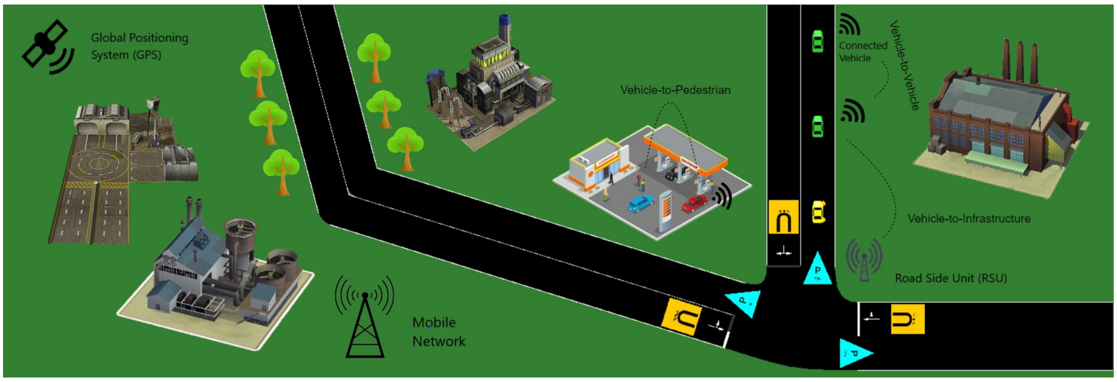

Figure 1.1: ITS V2X communications [8].

- **Cellular Vehicle-to-Everything (C-V2X):** A cellular-based communication technology based on 3GPP standards that operates in the licensed LTE bands.

Spectrum management organizations, such as the US Federal Communication Commission (FCC), have recognized the importance of providing dedicated spectrum for ITS-based communications. In 1999, the FCC allocated a 75 MHz bandwidth of the 5.9 GHz band from 5850 to 5925 MHz for DSRC [9]. This bandwidth was later refined with a guard band of 5 MHz at the lower end, and divided into seven channels of 10 MHz each. However, in November 2020, the FCC issued a First Report and Order that reallocates a majority of the 5.9 GHz band away from connected vehicle technologies. The order reassigns the lower 45 MHz of the band (5.85-5.895 GHz) for unlicensed use, and designates the upper 30 MHz (5.895-5.925 GHz) for C-V2X technologies. The remaining 5 MHz guard band remains in place to protect against interference [10]. The decision to allocate only the upper 30 MHz of the band to C-V2X technologies is seen by some as favoring cellular-based technologies over DSRC.

Instead in Europe, the band from 5875 to 5905 MHz was selected by the European Commission for ITS applications in 2008 [11]. Later, the European Conference of Postal and Telecommunications Administrations (CEPT) harmonized the band by extending it to go from 5855 to 5925 MHz [12]. The current spectrum allocation was designed based on technical recommendations TR 102 492-1 [13] and [14]. In this allocation, the frequency range from 5855 to 5875 MHz is assigned for non-safety related applications, while the range from 5875 to 5885 MHz is reserved for road safety and traffic-efficiency applications. The range from 5885 to 5905 MHz is designated for critical road-safety applications, and the range from 5905 to 5925 MHz is reserved for road-safety and traffic-efficiency applications.

Ensuring co-existence between DSRC and C-V2X technologies in the ITS band

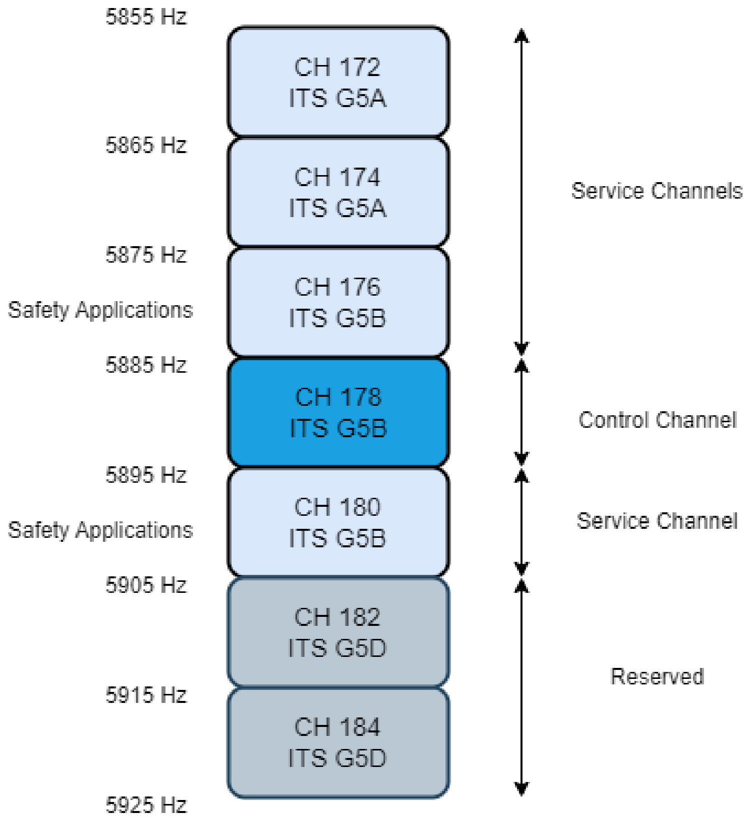

Figure 1.2: EU spectrum allocation for the 5.9 Ghz band.

requires careful consideration of the distribution of the band for each technology. Different approaches can be utilized to address this issue, including the approach suggested by [15], which as this thesis focuses on the European scenario. In this work, a possible three steps solution to ensure the co-existence of DSRC and C-V2X technologies is presented.

It's important to understand the limitations and opportunities of each protocol in order to make informed decisions about which one to use in a given vehicular networking scenario. In the following section a deeper analysis of the different DSRC and C-V2X protocols is made.

1.3 DSRC-based Protocols

1.3.1 WAVE

The IEEE WAVE (Wireless Access in Vehicular Environments) protocols are designed specifically for wireless communication in vehicular environments and include the IEEE 1609 family of standards [16][17][18][19], which define the message formats, security mechanisms, and networking protocols needed for V2V and V2I communication. Besides, WAVE contains the IEEE 802.11p standard, which specifies the physical and MAC layer. Moreover, The IEEE 802.2 at the Logical Link Control (LLC) layer is also included in the WAVE protocol stack.

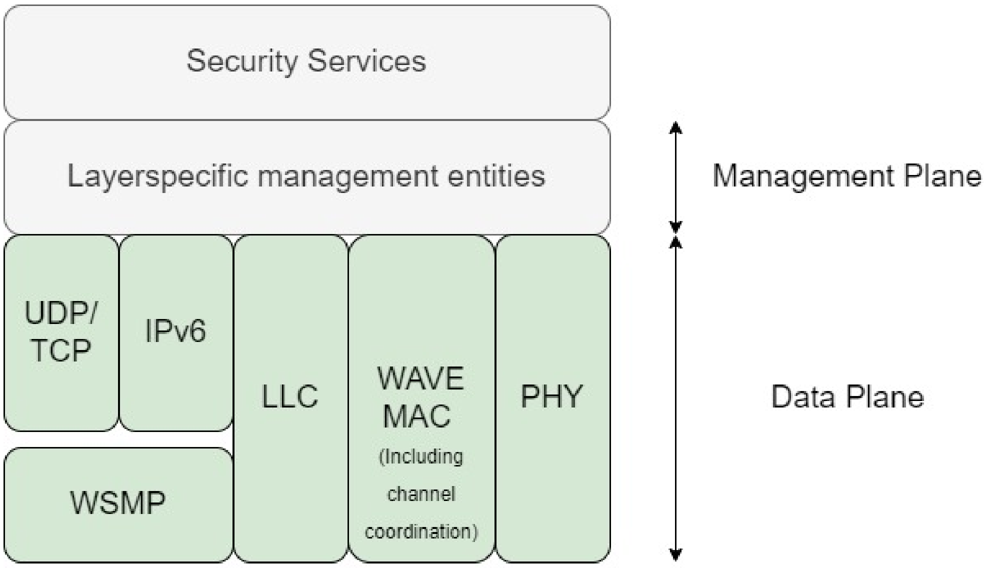

Figure 1.3: WAVE protocol stack [16].

These standards define the specifications for how applications that use WAVE will function within the WAVE environment. The IEEE 1609.1 standard defines the management activities for WAVE, while the IEEE 1609.2 standard defines the security protocols. The IEEE 1609.3 standard specifies the network-layer protocol for WAVE. The IEEE 1609.4 standard, which resides above the 802.11p physical layer protocol, supports the operation of higher layers without the need to deal with physical channel access parameters. This allows for multi-channel operation and channel coordination between WAVE devices [7]. However, the higher layers of the OSI model, including the Application, Presentation, and Session layers, are not officially specified for WAVE.

Figure 1.3 illustrates the components of the WAVE protocol stack. Is consists of two planes: the data plane and the management plane. The data plane is responsible for carrying higher layer information, and the management plane is responsible for managing and configuring the components of the WAVE protocol stack, including the data plane. The data plane and management plane work together to enable the efficient and secure transfer of data in the WAVE environment.

Transport and Network Layers

IEEE 1609.3 is a standard that specifies the networking protocols and interfaces for WAVE systems. It defines two data plane protocol stacks that share a common lower stack at the data link and physical layers.

The Wave Short Message Protocol (WSMP) allows applications to have more control over the physical characteristics of the messages they transmit. In WSMP, the source application provides a Provider Service IDentifier (PSID) that uniquely identifies it and the MAC address of the destination device, which can be a group address. The PSID is used to ensure that the message is delivered to the correct receiving entity. If the PSID value in a received message header represents a service that is not of interest to the WSM recipient, then the corresponding WSM data field is not processed.

In addition, the WAVE standards support IPv6 as the network layer protocol. IPv6 was selected over IPv4 due to its larger address space, which helps to address the scalability issues associated with IPv4. The WAVE standards do not specify which transport and higher layer protocols should be used over IPv6. However, the IP suite and its popular transport protocols, User Datagram Protocol (UDP) and Transmission Control Protocol (TCP), are supported.

In the WAVE system, the Management Plane is responsible for providing layer-specific functions necessary for the correct operation of the system. The WAVE Management Entity (WME) services are associated with the various data plane entities and provide functions such as time synchronization for channel coordination and processing service requests from higher layers. One of the key functions of the Management Plane is the generation, monitoring, and management of WAVE Service Advertisements (WSAs). The WME is responsible for generating and monitoring WSAs, which are typically sent periodically. However, the transportation of the WSAs in the way requested by the WME, is done by WSMP, which resides in the data plane [16].

Data-Link layers

The Logical Link Control (LLC) sublayer of the Data Link Layer in the WAVE protocol stack distinguishes between the two upper stacks, IPv6 and WSMP, based on the EtherType field in the LLC header. The EtherType field is a 2-octet field that specifies the type of network protocol used above the LLC sublayer. In the WAVE protocol stack, the EtherType field is used to identify whether the upper layer protocol is IPv6 or WSMP. The hexadecimal values 0x86DD and 0x88DC are used to indicate IPv6 and WSMP, respectively. It's worth noting that the usage of the EtherType field is specified in IEEE 802.2, but IEEE 1609.3 specifies its usage in WAVE devices [16].

While the WAVE protocol stack is built on top of the IEEE 802.11p standard for both the MAC and Physical Layers, IEEE 1609.4 specifies MAC sublayer extensions to the 802.11p standard to further extend the functionality of WAVE [19]. One of these extensions is channel coordination features to support multi-channel operation.

802.11p

Finally, as already stated, the IEEE 802.11p standard defines the Physical Layer (PHY) and Medium Access Control (MAC). It was designed specifically for use in vehicular environments, where wireless communication links can be rapidly changing and where fast and reliable communication is crucial. Besides, It also ensures interoperability between different types of wireless devices, allowing for seamless communication between vehicles, infrastructure, and other devices.

IEEE 802.11p is indeed based on the physical layer of IEEE 802.11a, which uses a wider 20 MHz channel bandwidth. The reduction to 10 MHz in 802.11p is to allow for better channel reuse and to minimize interference between channels, and to avoid multi-path fading and doppler effect phenomena resulting in Inter-Symbol Interference [20]. Orthogonal Frequency Division Multiplexing (OFDM) is used to enable high data rates from 3 Mb/s to 27 Mb/s and robustness against multi-path fading and interference. Moreover, OFDM is based on 64 orthogonal subcarriers and its different modulation schemes (BPSK, QPSK, 16QAM and 64QAM) allow for flexibility in adapting to different channel conditions.

Furthermore, the Outside the Context of a BSS (OCB) is a new mode of operation supported by 802.11p in addition to ad hoc and infrastructure modes, which allows for communication outside the context of a BSS. It is useful in vehicular environments where nodes may not always be within range of a fixed infrastructure. The use of 802.11e-based priority schemes and Access Categories (AC) helps to prioritize different types of messages, such as safety-critical messages, over non-safety-critical ones. This can help ensure that important messages are transmitted in a timely and reliable manner, even in high-traffic environments. From lowest priority to highest the ACs defined are [21]:

- AC_BK: Background
- AC_BE: Best Effort
- AC_VI: Video
- AC_VO: Voice

1.3.2 ITS-G5

ITS-G5 is the European standard for vehicular communications since 2007, which is based on the WAVE architecture and uses IEEE 802.11p as the base standard as defined in [22]. However, ETSI has also been working to integrate new access technologies such as LTE-V2X to the stack. This integration is aimed at enhancing the reliability and efficiency of vehicular communication systems, and ETSI has provided guidelines, as outlined in [23] for the interconnection of higher layers with the ITS-G5 protocol stack to facilitate this integration.

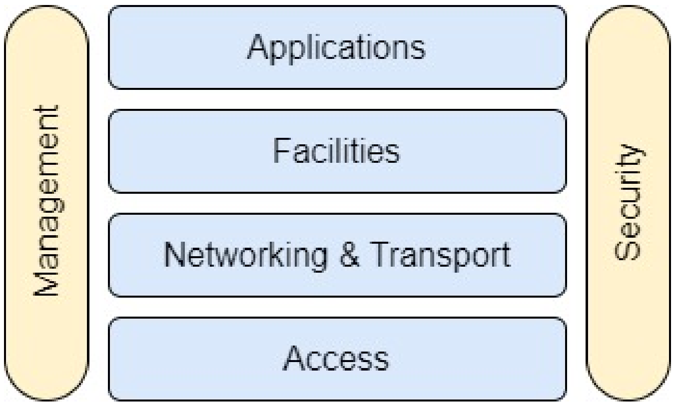

Figure 1.4: ITS station protocol stack.

The protocol stack of an ITS station specified in [24] follows a similar approach of the ISO/OSI reference model defined in ISO/IEC 7498-1, with different layers responsible for specific tasks in vehicular communication. In the Figure 1.4 can be seen that four data planes layer are defined, namely:

- **ITS Applications layer:** It is explained in [25] [26] [27] where technical requirements for Road Hazard Signalling (RHS), Intersection Collision Risk Warning (ICRW) and Longitudinal Collision Risk Warning (LCRW) are specified respectively.

- **ITS Facilities Layer:** Defined in [28] and EN 302 637- 2/3 [29] [30]. The Cooperative Awareness (CA) and Decentralized Environmental Notification (DEN) basic services are explained together with the format of the message managed by them for V2X communications.

- **ITS Networking and Transport Layer:** Defined in [31] [32] [33] [34] [35]. In these documents the GeoNetworking and Basic Transport Protocol are defined. These correspond respectively to the layer 3 and 4 of the ISO/OSI reference stack.

- **ITS Access Layer:** It is defined in [22] where the outlines for the physical and MAC sub-layer are specified, and in [36] and [37], where the mechanism for Decentralized Congestion Control (DCC) is defined.

Moreover, 2 vertical layers are defined:

- **ITS management entity:** Its task is to configure the ITS station, cross-layer information exchange among the different layers and other tasks [33].
- **ITS security entity:** It is responsible for security and privacy services, including management of identities and security credentials, secure messages at different layers of the communication stack, and aspects for secure platforms (firewalls, security gateway, tamper-proof hardware)[33].

In the following a brief explanation of the layers of the stack is reported.

Application and Facilities layers

The ITS-G5 stack standardize a more extended scope than WAVE, with the reference layers 5, 6 and 7 of the ISO/OSI stack (i.e. Session, Presentation and Application) also standardized. As far as it goes for the Application layer, for safety use cases ETSI defines three main applications utilizing the exchange of CAMs (Cooperative Awareness Messages) and DENMs (Decentralized Environmental Notification Messages). In [25] the Road Hazard Signaling (RHS) is introduced as a means of increasing awareness between ITS stations (ITS-S 3.1.2) and ITS stations with the driver. The RHS has two modes: the originating mode and the receiving mode. The originating mode enables ITS-Ss to detect and signal road hazards to other ITS-Ss in the vicinity, while the receiving mode enables ITS-Ss to alert drivers of relevant road hazards. Furthermore, [26] also describes the ICRW application which is designed to detect potential collision risks within an intersection area. This application identifies several types of collision risks including crossing collisions, traffic sign violations, collisions involving Vulnerable Road Users (VRU), and rear-end collisions. Likewise, [27] describes the LCRW (Longitudinal Collision Risk Warning) application, which is designed to detect potential collision risks on the longitudinal axis of a vehicle's direction of travel. This application identifies several types of collision risks, including: forward collision, forward/side collision and frontal collision.

Next step in the ITS-G5 stack is the Facilities layer, which provides support to ITS applications by allowing them to share generic functions and data based on their specific functional and operational requirements. [24] provides more detailed information on the facilities layer and how it is used to support ITS applications.

According to [28], the Facilities layer covers the three upper layers of the OSI reference model, including the Application layer, Presentation layer, and Session layer. The Facilities layer is organized into three sub-layers, which are:

- **Application support facilities:** This sub-layer provides support for application-specific functions and services for the ITS Basic Set of Applications (ITS BSA), such as message exchange, data management, and event handling. The CA (Cooperative Awareness) and DEN (Decentralized Environmental Notification) basic services managing the CAM and DENM are some examples of the application support facilities.

- **Information support facilities:** This sub-layer provides support for information-specific functions and services, such as data encoding and decoding, data compression and decompression, and data encryption and decryption. Local Dynamic Map (LDM) is an example of these facilities.

- **Communication support facilities:** This sub-layer provides support for communication-specific functions and services and session management, such as message routing, network addressing, and quality of service (QoS) management, and also providing the message dissemination requirements to the network and transport layer.

The messages that have to be disseminated by the ITS Networking and Transport layer are provided by the CA and DEN basic services. Here we go through a brief description of these services. The CA basic service is a facilities layer entity that operates the CAM protocol and provides two main services: sending and receiving of CAMs [29]. CAMs are generated periodically, with the generation frequency determined based on changes in the ITS-Ss status, such as changes in position or speed. The frequency also takes into account the radio channel load, as determined by the DCC in the ITS Access layer. Lastly, CAMs are transmitted in a single-hop manner, meaning that they are sent directly between ITS-Ss that are within radio range of each other.

On the other hand as described in [30], The DEN basic service is an application support facility that constructs, manages, and processes DENMs. Unlike the CAM protocol, the construction of a DENM is not triggered periodically, but rather by an ITS-S application when an abnormal traffic condition or road hazard is detected. DENMs contain information related to the road hazard or abnormal traffic condition, including its type and location. They are typically disseminated to other ITS-Ss that are located in a geographic area through direct V2V or V2I communications.

Networking and Transport layers

The ITS networking and transport layer includes protocols that facilitate data delivery between ITS stations and other network nodes [33]. One of the networking modes that is particularly relevant to ITS is GeoNetworking, which enables efficient and reliable communication among vehicles, roadside infrastructure, and other network nodes in a geographic region. ITS also supports the use of IPv6, which provides improved addressing and routing capabilities compared to IPv4. The transport layer protocols used in ITS depend on the networking mode being used. For GeoNetworking, ITS-G5 defines the Basic Transport Protocol, which is designed to provide reliable, connection-oriented data transfer. For IPv6 networking modes, existing transport protocols such as UDP and TCP can be used. In addition, IPv6 networking in ITS includes methods to ensure interoperability with legacy IPv4 systems [24].

Access layers

As mentioned before, the ITS Access Technologies use IEEE 802.11p as the base standard for the MAC and Physical layers, although later extended to support also LTE-V2X [23], which provides the radio communication capabilities necessary for VANETs. However, to address the challenges of highly dynamic and congested vehicular environments, ITS-G5 extends IEEE 802.11p with additional features such as decentralized congestion control (DCC). DCC is designed to mitigate congestion in the communication channel by shaping the data traffic injected by each communicating station [36]. In addition, another strategy implemented by the ITS-S is assigning priorities between messages and removing low priority ones in the case that application requirements exceed allotted resources. Finally, the cross-layer operation of the DCC mechanisms for ITS-S is described in [37] while the access layer point of view of the DCC mechanisms are described in [36].

1.4 Cellular-based Protocols

The standardization of C-V2X technology by 3GPP in Release 14 [38] has generated significant interest in cellular-based technologies for vehicular communications. While IEEE 802.11p has been around for longer and is specifically designed for VANETs, C-V2X offers several promising features that make it an attractive option. Some of the features included are increased radio coverage, well-established cellular infrastructure, and higher penetration rate due to the widespread adoption of smartphones.

LTE-V2X

LTE-V2X, introduced in 3GPP's Release 14, builds upon the Proximity Service (ProSe) capabilities defined in Releases 12 and 13. ProSe enables device-to-device (D2D) communications, allowing devices in close proximity to communicate directly with each other. Hence, LTE-V2X introduces a new channel in the Physical layer known as the sidelink. The sidelink is specifically designed to cater to the requirements of vehicular use cases, supporting communication between nodes that are moving at high speeds and in high-density environments.

In order to enable Vehicle-to-Everything (V2X) communications, 3GPP has defined two modes of operation in the [38]:

- **V2X Communication over PC5 Interface:** The PC5 interface directly connects User Equipments (UEs) to enable V2X communication. This mode utilizes sidelink technology when the UE is within the coverage of the LTE network. It is known as Mode 3. In this mode, the UE transmits V2X messages over the air, and these messages are received directly by other UEs in proximity. It also supports communication when the UE is outside the network coverage (Mode 4).
- **V2X Communication over LTE-Uu Interface:** The LTE-Uu interface connects UEs with the eNB (E-UTRAN NodeB), which acts as the base station in LTE networks. In this mode, UEs receive V2X messages (either unicast or broadcast) via the downlink, while transmitting V2X messages via the uplink. Unlike PC5-based communication, V2X communication over LTE-Uu is supported only when the UE is within the network coverage.

In Release 14, the focus of the work in 3GPP was primarily on providing data transport services for basic road safety services in V2X communications. These included Cooperative Awareness Messages (CAM) and Decentralized Environmental Notification Messages (DENM), as mentioned in [39]. In Release 15, 3GPP continued its efforts to enhance support for V2X scenarios and introduced new requirements to address advanced use cases. These included: Vehicle Platooning, Advanced Driving, Extended Sensors, and Remote Driving. Additionally, Release 15 introduced key functionalities to improve the overall performance of V2X communications. These included the support of Carrier Aggregation (CA) for transmission mode 4 and support for 64-QAM modulation, as it is stated in the [39].

5G V2X

5G V2X is not intended to replace LTE-V2X, but rather to supplement C-V2X technology by supporting use cases that cannot be adequately addressed by LTE-V2X. 5G NR V2X is specifically designed to meet the diverse requirements of V2X applications, including varying latency, reliability, and throughput needs. While

LTE-V2X primarily focuses on periodic traffic, 5G NR V2X caters to both periodic and aperiodic message transmissions. A large number of use cases in 5G NR V2X rely on the reliable delivery of aperiodic messages. Additionally, while some V2X use cases require broadcast transmissions to all vehicles in the vicinity, others, such as vehicle platooning, benefit from targeted transmissions to specific subsets of vehicles (UEs) involved in the scenario. In order to enhance the PC5 interface, which facilitates direct V2V and V2I communication, 5G-V2X introduces several modifications. These include: Modulation and Coding Scheme (MCS) extended to 64-QAM, Use of frequencies above 6 GHz, Use of Multiple-Input Multiple-Output (MIMO) antennas, and Reduction of Transmission Time Interval (TTI) to 0.5 ms.

Chapter 2

Local Dynamic Map

2.1 Introduction

The Local Dynamic Map (LDM) defined in [40], plays a crucial role in cooperative ITS. It serves as a fundamental component that supports a variety of ITS applications by storing and managing information about objects that affect or are involved in traffic. In the context of the EC's (European Commission) 2009 ICT Standardisation Work Program, the Local Dynamic Map becomes significant for the development of technical standards and specifications. These standards and specifications ensure the consistent deployment and interoperability of cooperative systems and services across different regions and stakeholders.

In the ITS architecture defined by the ETSI, the LDM is recognized as a key function within the ITS station facilities layer. The LDM relies on data from three important message types: CAMs, Collective Perception Message (CPMs) and DENMs. In addition, the Basic Set of Applications (BSA) are defined in the ITS architecture, which is a collection of applications that make use of the information stored in the LDM. Some of the key classes of applications included in the BSA are:

- Driving assistance - Co-operative awareness.
- Driving assistance - Road Hazard Warning.
- Speed management.
- Co-operative navigation Location based services.
- Communities services.

- ITS station life cycle management.

2.1.1 The LDM

Information about the local environment is crucial in cooperative ITS. These systems rely on data about both moving objects, such as nearby vehicles, and stationary objects, such as road signs and infrastructure. In cooperative ITS, different applications often require access to common information about the local environment. The LDM serves as a repository for relevant information about the local environment, including both the static infrastructure and dynamic elements.

The LDM is indeed a conceptual data store that resides within an ITS Station (ITS-S). Its purpose is to store and manage information that is relevant to ensuring the safe and efficient operation of various ITS applications. The LDM receives data from a variety of sources, including vehicles, infrastructure units such as Road Side Units (RSUs), traffic centers, and on-board sensors as can be seen in Figure 2.1. To access the data stored in the LDM, there is typically an interface provided. Mechanisms are put in place to control and manage secure and safe access to the data stored within the LDM. By providing access to information on the surrounding traffic and RSU infrastructure, the LDM serves as a centralized source of data for all ITS applications that require it.

2.1.2 LDM within the ITS architecture

Cooperative ITS encompass V2V, V2I, and infrastructure-to-infrastructure (I2I) communications. These communication modes facilitate the exchange of information between different entities within the transportation system, enabling cooperative functionalities and enhancing overall system performance. Therefore, ITS stations that are part of the roadside infrastructure can differ from vehicle-based ITS stations primarily in terms of their connected sensors. Roadside equipment, being a part of the fixed infrastructure, often has access to more dedicated and specialized sensors that are integrated into the road network itself.

According to the current ITS station reference architecture, the LDM is positioned within the facilities layer, specifically in the information and application support domain. Details of the facilities layer are presented in Figure 2.2.

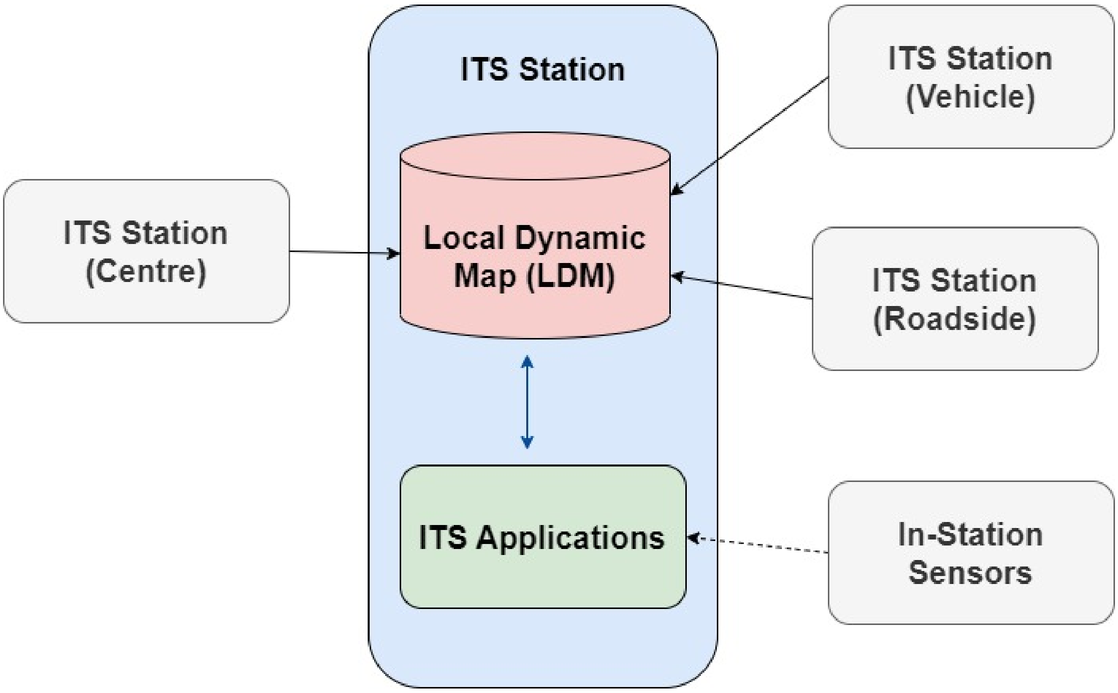

Figure 2.1: Information sources for LDM.

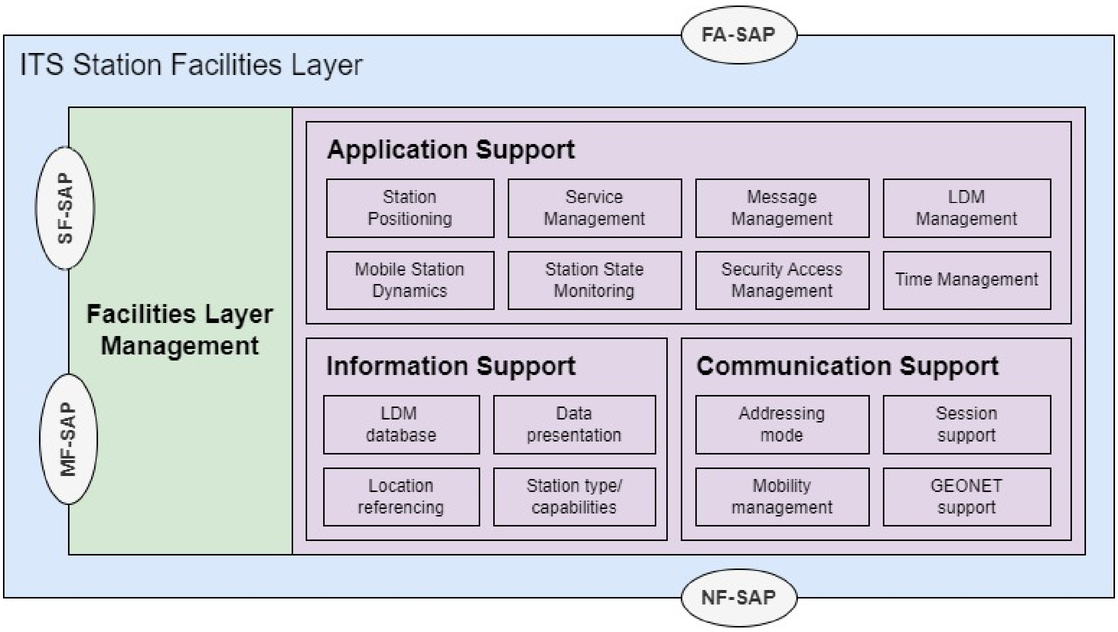

Figure 2.2: ITS Application/Facilities overview [40].

2.2 Applications and Use Cases

The analysis of ITS applications is based on following applications:

- Driving assistance -Co-operative awareness (CA).
- Driving assistance - Road Hazard Warning (RHW).
- Co-operative speed management (CSM).
- Co-operative navigation (CN).
- Location based services (LBS).
- Communities services (CS).
- ITS station life cycle management (LCM).
- Transport related electronic financial transactions (road tolls).

2.2.1 Application Analysis

Information Elements

By categorizing the information in the LDM into distinct types, the architecture ensures that different types of data are managed and utilized effectively by the ITS applications. There are 4 different classes of data [40]:

- **Type 1 - Permanent Static Data:** The purpose of Type 1 data is to provide static information on real-world objects that are relevant to the road network and traffic flow. Some Examples of Type 1 Data are: Lane (precise) road topography, Position of permanent local point of intrest (POI) and services (including public car parks), Position of local toll collection points, Statutory speed limit descriptor. No permanent, static information is required to be stored in the LDM. Usually provided by a map data supplier.
- **Type 2 - Transient Static Data:** The purpose of Type 2 data is to provide information about the real-world objects associated with the roadside infrastructure. Some Examples of Type 2 Data are: Traffic signals and traffic signs, Position and meaning of new signs not in the pre-loaded map data, Position of new points of interest (POI) and services (including public car parks), Toll charge for each collection point.

- **Type 3 - Transient Dynamic Data:** This data describes real-world information with a dynamic behavior, as it changes over time and has an impact on the efficiency of traffic. Some Examples of Type 3 Data are: Location and dimensions of road works, Temporary speed limit descriptor, Current status of traffic signals, Location and dimensions of hazard (including stationary vehicle and weather conditions), Temporary changes in lane or road direction restrictions, Designed progression speed through linked traffic signals, Position of temporary points of interest (including public car parks), Current status of all permanent and temporary local parking facilities, Position and meaning of temporary signs not in the preloaded map data.

- **Type 4 - Highly Dynamic Data:** Type 4 data includes information about ITS stations within the vicinity, such as vehicles and dynamic traffic signs. An Example of Type 4 Data is: Current speed, position and direction of all ITS Stations within range of the host like CAMs.

The LDM does not typically include Type 1 data. In many cases, not all ITS stations require Type 1 data. If a particular application within an ITS system, such as a navigation application, needs access to Type 1 data (e.g., map data), it can optimize and store the required data specifically for that application's use. The reason for this is that defining a common map data format and specifying standard interfaces to access Type 1 data that meet the requirements for all ITS stations is currently not feasible.

The LDM data can be relevant for applications that make use of Type 1 data, and therefore, location referencing data becomes necessary for relating Type 2, Type 3, and Type 4 information to the Type 1 map data. Location referencing is a complex operation that involves associating dynamic and transient data with the static map data. However, it's important to note that not all ITS applications that potentially use the LDM require location-referenced information. Therefore, while location referencing is essential for certain applications, its use is not mandatory for all ITS applications utilizing the LDM. The Information elements required by each use case are mentioned in [40].

Functionality

The LDM is located within the ITS facilities layer and serves as a key component that provides functionality required by multiple applications. The LDM internal functions are identified by the functional requirements including: receive incoming CAM/CPM/DENM and perform plausibility check on them, store and protect relevant information for required time, provide accurate information to authorized applications as requested and in a timely manner, and enable applications to store and protect processed information in order to share their results with other applications. In addition to these requirements, there exist non-functional requirements, such as reliability and scalability. Although, It may be necessary to consider the reliability of an ITS station in general (and the LDM in particular) as a potential regulatory requirement supported by European standardization [40].

The plausibility check of the receiving information from incoming ITS CAM CPM DEM messages needs to be done by the LDM. Also, Notification mechanisms with application-defined trigger conditions can be included in the LDM. In addition, applications have Read Write access to the LDM and mechanisms are defined to let the applications update the LDM after processing their information. Last but not least, the host information will not be in the LDM.

2.2.2 Use Cases

Each application contains one or more use cases. All use cases - including a short description and their origin are provided in [40]. The LDM covers a wide range of use cases which are taken from the ITS BSA, SAFESPOT, CVIS, COOPERS, and the Car-to-Car Consortium Manifesto [40]. Some examples of these use cases are: Emergency vehicle warning, Slow vehicle indication, Across traffic turn collision risk warning, Merging Traffic Turn Collision Risk Warning, Co-operative merging assistance, Intersection collision warning, and Theft related services/After theft vehicle recovery. They have been classified in different application classes such as: Activity road safety, Cooperative traffic efficiency, Co-operative local services, Global internet services.

2.2.3 Location Information

In the LDM, location information plays a crucial role in describing the position and extent of various objects. Each LDM object consist at least of one WGS84 coordinate pair. There are three distinct types of location information:

1. **Point Location:** This refers to a specific point on the map, representing the position of an ITS station or any other object with a single location.

2. **Segment Location:** Segment location describes a linear extent on the road network, such as the position and extent of a traffic jam or a road segment with a specific attribute.

3. **Area Location:** Area location refers to a geographic area, such as a weather situation or a designated zone.

For example, consider a temporary speed limit that is applicable between a start position and an end position. In order for applications to correctly interpret and apply this speed limit, it is important to provide information about the points along the road between the start and end positions. This could be achieved by explicitly specifying the relevant points or coordinates that define the segment of the road network affected by the speed limit.

2.3 Architecture

Standardizing an Application Programming Interface (API) for the LDM is crucial to facilitate seamless interaction between applications and other components of the ITS communications architecture. The LDM architecture is depicted in the Figure 2.3. The ITS reference architecture specifies two main components of the LDM:

- **LDM Management**
- **the Data Store**

2.3.1 Requirements

The functionalities of the LDM are provided by the internal modules of the LDM Management: Subscription/Notification module, Information Management module, and Information Access module.

Each module delivers at least one of the functionalities mentioned under their name:

- **Subscription/Notification functionalities:** - handling subscription/unsubscription requests for notification coming from applications; - filtering mechanisms to allow an application specific subscription to information; - sending notification to the subscribed application; - providing requested information together with a notification;

- **Information Management functionalities:** - receiving information from CAM, CPM or DENM; - storing received information in the LDM data store; - handling LDM maintenance (such as discarding information that are irrelevant or performing clean-ups); - handling application requirements;

- **Information Management functionalities:** - receiving requests from application information; - decoding and filtering information requests; - ensuring

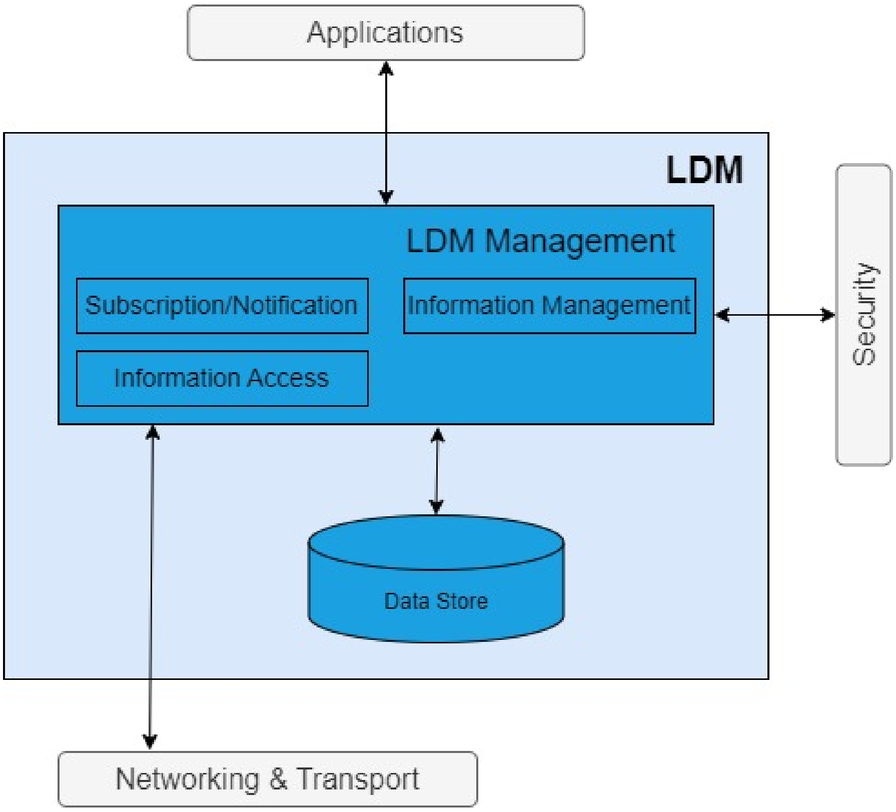

Figure 2.3: LDM architecture [40].

that security constraints are obeyed; - retrieving information from the LDM data store; - passing back information to the requesting application;

In addition to functionalities mentioned above, each component of LDM Management is able to access the Data Store directly and perform following actions: - storing relevant information; - supporting insertion, update and delete functions;
Some application layer roles which are LDM access related are: - subscribe to notification services; - process the retrieved information and write the result back in the LDM; - set the LDM management rules for managing information that is written in the LDM by the application;

2.3.2 API

The LDM has three main interfaces that facilitate communication and data exchange with other components of the ITS architecture: • LDM - FA-SAP (Applications) • LDM - NF-SAP (Networking) • LDM - SF-SAP (Security)

LDM - NF-SAP

The LDM - NF-SAP interface serves as a connection between the LDM and the communication functions of the ITS station. It allows the LDM to receive incoming messages such as CAM, CPM, DENM and TPEG, as well as other traffic-related information.

It's important to note that the LDM does not provide messages to the communication functions. Instead, its primary role is to receive and process incoming information from authenticated sources. The authentication of the source is typically handled by the ITS communication functions.

Within the LDM, a first level of plausibility checking is performed on the received messages. This involves verifying the consistency of the information within the CAM, such as the time-stamp and location information, compared to recent messages from the same ITS station and other nearby sources. The purpose of this plausibility checking is to ensure that the received information is reliable and consistent with the existing data stored in the LDM.

When there is an update to the LDM object information, which includes the associated situational information, the LDM undergoes a process involving the incoming messages:

1. The messages are decoded and converted into LDM objects.
2. The LDM checks whether the messages imply updates to existing LDM objects or the insertion of new objects into the LDM.
3. The LDM inserts the new objects or updates the existing ones accordingly.

LDM - FA-SAP

The LDM - FA-SAP interface plays a crucial role in enabling applications to interact with the LDM and access its data. This interface provides functions that allow applications to manage LDM access and LDM data, retrieve data, and modify data.

The LDM access management functions enable applications to perform the following tasks: - Retrieve an overview of the services offered by the LDM; - Grant access rights to the LDM functionality;

The data management functions provide capabilities for applications to: - Set and retrieve data maintenance settings; - Subscribe and unsubscribe to notification functions; - Set notification settings; - Send notifications to subscribed applications;

The data modification and access functions enable applications to perform the following actions: - Add, update, and delete data; - Read data including filtering options;

Finally, the LDM - FA-SAP interface is designed to handle requests from multiple applications simultaneously. In scenarios where there are multiple applications requesting data from the LDM, it is important to prioritize the handling of these requests to ensure that safety-critical functions are given precedence.

LDM - SF-SAP

The LDM - SF-SAP interface enables the access to the ITS station security functions. This interface enables the LDM to implement information access control functions to prevent potential abuse of LDM data by third-party ITS applications.

To ensure secure access to LDM information, it is necessary for applications to go through an authentication and authorization process. This process verifies the identity of the application and determines whether it is authorized to access specific LDM information. The authentication mechanism is provided by the ITS Security Functions (SF), and the LDM utilizes this mechanism to grant or refuse access to the requested information.

2.3.3 Static maps

In order to ensure accurate referencing of information between the LDM and the static digital map, mechanisms for location referencing are crucial. This is particularly important because absolute positioning information from satellite-based systems and other sensors may have inherent inaccuracies.

Dynamic location referencing is the process of encoding the dynamic position of an object in a digital road network and subsequently locating that position in another map. To support this process, two standardized methods are widely recognized: OpenLR, which is an industry standard, and Agora-C, an international standard developed and published by ISO. it is advisable to store the received location referencing information within the LDM.

Chapter 3

Collective Perception Message

3.1 Introduction

The Collective Perception Service (CPS) is designed to facilitate the exchange of information among ITS-Ss regarding the presence of road users and obstacles. It enables ITS-Ss equipped with local perception sensors like radars and cameras to share data about the objects in the surrounding that they detect. The purpose of this service is to enhance the situational awareness of individual ITS-Ss by augmenting their knowledge base with information contributed by other ITS-Ss [41].

The CPS introduces the CPM as a mean of sharing information about detected objects by the ITS-S that is disseminating the message. The CPM contains essential details about the disseminating ITS-S itself, including its sensory capabilities, as well as the objects it has detected. For this purpose, The CPM is designed to provide a standardized format for describing detected objects within the reference frame of the disseminating ITS-S. Furthermore, To optimize the communication load, the CPM is transmitted cyclically with adaptive message generation rates.

3.1.1 CP service in the LDM

As already mentioned, CPMs play a crucial role in the creation and maintenance of the LDM. They enable the exchange of object information among ITS-Ss, contributing to a shared situational awareness and facilitating cooperative perception. Thus, the LDM built upon the received CPMs, provides an up-to-date and comprehensive representation of the dynamic environment, supporting various advanced applications and services in the ITS.

The sensors provide us with Raw Sensor data, which is not logical to be sent by the CPM, because they may get so huge. For this purpose, there are Sensor specific low-level object fusion systems provided to list the objects as detected by the measurement of the sensor. These implementations are specific to a sensor, and the result is going to be a state space representation of an objects which is specific to a timestamp. A responsibility of object fusion mechanism is to provide predictions at timestamps with no measurements. Other tasks of this mechanism is to keep a list of objects, associate objects from LDM to the list, merge the prediction and the update measurements, housekeeping like adding new state space, updating objects, removing objects, can also classify objects. These tasks are preferred to be done by the low level system, as it is more likely to avoid filter cascades, but CPS may also select itself the objects from a high level fused object list [41].

3.1.2 CPM use cases

Some use cases [41] where this service is beneficial are Detection of the Non-Connected Road Users, Detection of Safety-Critical Objects, and CAM Information Aggregation in Increase Awareness and Awareness about ITS-communication enabled persons on the road. Road users who are not capable of communicating directly can only be perceived by the environment perception sensors of other vehicles or infrastructure equipped with sensing capabilities. Without the CP service, the awareness range of such road users would be limited to the field of view of individual sensors, which can be obstructed by obstacles like buildings or other vehicles. In these use cases the objects (Vehicles, Cyclists, Pedestrians, etc) are detected by ITS-Ss (Vehicle or Roadside ITS-S equipped with sensors). Then, the transmitted CP messages can be received by ITS-Ss (with or without sensors) that can be vehicles, drivers, cyclists, pedestrians, or ITS central systems. The goal is to detect all non-connected road users and transmit this information to all surrounding ITS stations, besides increasing the accuracy of any road user information.

In addition to road users who are unable to communicate, there can be other safety-critical objects or hazards present on or near the street that pose a risk to road users. These objects can include lost cargo, fallen tree limbs, debris, or any other potential dangers. Furthermore, Intersections are particularly challenging areas where increased awareness range is beneficial for the safety of road users. However, in situations with a large number of ITS stations present, the observed channel load can increase, potentially reducing the awareness range. Hence, utilizing roadside ITS-Ss with CP services at intersections can improve safety by providing early recognition of approaching vehicles.

3.1.3 CPM Dissemination Concept

In this section the generation rules of CPM are explained. CPMs are generated for surrounding objects with sufficient level of confidence, which needs to contain as detailed information as possible, and get updated as often as possible. But on the other hand, from communication stack point of view, channel utilization should be reduced. In this regard, the proposed CPM generation method aims at finding the trade-off between these criteria.

For transmitting CPMs, point-to-multipoint communication, sepcified in ETSI EN 302 636-3 should be considered. Moreover, the Modulation and Coding Scheme (MCS) my affect the resulting channel usage. In cases, where large packets are needed (For instance, where an ITS-S senses multiple objects), utilizing MCS will increase the bandwidth efficiency and lower the channel occupancy. It will be activated with the activation of the ITS-S and terminates with its deactivation. The minimum time passed between generation of consecutive CPS should be equal or larger than T_GenCpm, which is limited between a minimum and maximum value. In case of the ITS-G5, T_GenCpm should be managed according to the channel usage requirements of Decentralized Congestion Control (DCC) as specified in ETSI TS 102 724. Hence, DCC may drop some CPM messages, but by giving feedback to the CPM generation function, it may result in adding the objects of the dropped message inside the new one. In case of LTE_V2X PC5, this value should be managed considering the congestion control mechanism defined by the access layer in ETSI TS 103 574.

In case the object is not a person or an animal, the conditions to consider the object for transmission by the CPM is one of the following:

- If the object has been detected after the CPM generation event
- If the distance of the object with respect to its last position exceeds 4 m
- if the difference of the speed of the object with respect to its previous speed exceed 0.5 m/s
- if the orientation of the vector of the object with respect to its previous orientation is changed more than 4 degrees
- if the time elapsed since the last time this object is included in the CPM exceeds T_GenCpmMax

In addition, if objects belonging to this class are predicted to be included in the next event of the CPM generation, they should be included in the currently generated CPM to reduce the number of generated messages.

In the other case, if the object class correspond to the person or animal class the conditions to consider are:

- if the new object is detected after the last CPM generation event
- if the object list contains at least one object which has not been included in the CPM

In this case all the objects of class person or animal should be included in the currently generated CPM.

There are mechanisms implemented to avoid sending big messages. In case the size of the generated CPM exceeds a threshold, CP message segmentation needs to be done. Each message segment will be interpreted without the need to receive all the segments. All the segments have to indicate the same generation time, and it should be mentioned in the CPM that it consists of how many segments.

3.2 CP Service Analysis

The objects that can be shared by the CPM are either static (i.e. do not move but are on the driving lanes) or dynamic (i.e. move or have the ability to move). It means that the purpose of the CPMs is not to share nor to compare traffic-regulation information such as traffic signs and traffic light information. Therefore, map matching algorithms on the disseminating ITS-Ss shall be used for determining whether an object is located on a lane. Moreover, to compute the object confidence, each ITS-S implements an unanimous methodology. This helps to clearly interpret the confidence indications. This goes the same about the confidence of the free spaces. Each receiving ITS-S can combine the information available about the free space and the sensory capabilities of the transmitting ITS-S, to compute the free spaces. Thus, the confidence rate of a free space can be computed as the ratio of number of detected evidences of free space with respect to the total number of detection attempts within a specified time period.

3.2.1 Mitigation rules

In the situation where multiple ITS-Ss are perceiving the same object, redundant and unnecessary frequent updates about the same object will be broadcast, which will result in a higher network channel load, that may lead to frequent losses of CPMs. For this purpose, different predefined redundancy mitigation rules exist, that give the permission to the CP service to remove those objects meeting the rules. It is worth noting that these techniques should be enabled only in case that the observed channel load (e.g. channel busy ratio) is higher than threshold, in other cases CPM should include all the perceived objects that are full filling the CP message generation rules defined in the previous chapter. For instance, some of these techniques are Frequency-based Redundancy Mitigation Rule, Dynamics-based Redundancy Mitigation Rule, Confidence-based Redundancy Mitigation Rule, Entropy-based Redundancy Mitigation Rule, Object Self-Announcement Redundancy Mitigation Rule, and Distance-based Redundancy Mitigation Rule.

Utilizing the mentioned mitigation rules has its own advantages and disadvantages. On one side, it helps to reduce the channel utilization and message size, but on the other side, removing an object from the CPM when the transmitter is the only one sensing the object, or when trying to match the local data and the CPM objects, can cause problems for CP Service. Furthermore, using these rules can diminish data quality and also cause loss of CPMs; and all of this is done, while assuming that other surrounding ITS-Ss are performing the same or a similar rule, which may not always be the case and it will be another problem [41].

3.2.2 Sample Scenarios

To improve the effectiveness of the CPM and better understand its mechanisms such as generation rules and message composition, different simulations have been done by the standard. These simulations are based on 2 main setups and assess different aspects of the CP Service by evaluating main-metrics, such as the channel load and the generated awareness, the message generation rate and size, the effect of different message generation rules on the resulting channel load and on the generated awareness, the influence of DCC operations on CPM transmission, and the need for message segmentation.

First simulation study employs the simulation framework Artery, which couples the network simulator OMNeT++/OMNEST with the traffic simulator Simulation of Urban MObility (SUMO), and includes a complete ETSI ITS-G5 stack. So each vehicle associates to its own CP and CA service. Artery includes also radar sensors as local perception sensors to acquire information about neighbouring objects.

While the second simulation study employs ns3 discrete-event network simulator and SUMO. This scenario utilizes the same local perception sensors of the previous setup. The different CPM generation rules considered are static (2 Hz, and 10 Hz), dynamic and dynamic-LA, which is the dynamic one with the mechanisms mentioned in previous sections to reduce the number of the generated messages.

Furthermore, simulations has been done under various market penetration rates, and finally the effect of transmitting CPM on the same channel of CAM, with same priority, with lower priority and also on different channel than CAM, have been analysed.

The results of the simulations show that the dynamic generation rules are better than the periodic generation rules, as they deliver a better equilibrium between channel load and the awareness. In addition, the dynamic selection of the objects helps to decrease the message size while providing similar inter-object update times as periodic one. Moreover, even if the periodic approach performs better in terms of awareness, but it causes a higher channel load. For instance, a periodic sending of messages at 2 Hz may reduce channel load compared to the dynamic approach, but the awareness achieved is lower. Furthermore, range and field of view of local sensors plays a significant role on the channel load generated and awareness achieved.

It is also strongly suggested to send the CPM in a different channel than CAM, because by considering the effect of the variations of the market penetration rates, at lower values sending CPM with the same characteristics of the CAM results in a about twice channel utilization; At higher rates, as a consequence of more vehicles competing for channel access, a lot of CPM will be lost or not sent as the consequence of the DCC operations. As a matter of fact, in future it is also strongly recommended to send any other foreseen ITS message on a different channel than CAM [41].

3.3 CPM Structures

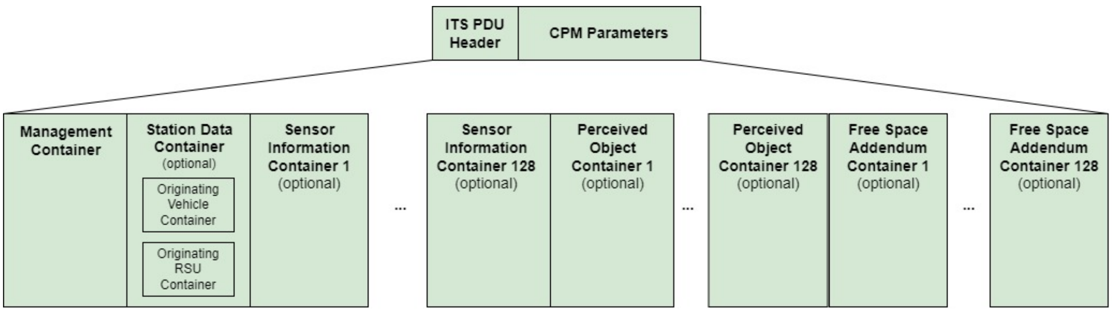

Figure 3.1: General Structure of a CPM [41].

In this section the CPM containers will be explained. As can bee seen in Figure 2.1, a CPM is constituted of one common ITS PDU Header and multiple containers. The ITS PDU Header is foreseen as [42].

The Management Container involves the station type, reference position and optionally information about the current message segment, regardless of which type of ITS-S disseminates a CPM. The reference point is for referencing objects in relation to a provided global position. For vehicles, it is the centre of the front side of the bounding box of the vehicle; And for RSUs, it is an arbitrary position on a road segment or intersection. In addition, the total number of the perceived objects is also provided inside the Management Container. It should be noted that The number of perceived objects by the transmitting ITS-S numberOfPerceivedObjects Data Frame (DF) does not have to be equal to the number of objects included in the CPM, because of segmentation, or already mentioned mitigation rules.

In the following, the optional containers of the CPM will be thoroughly explained.

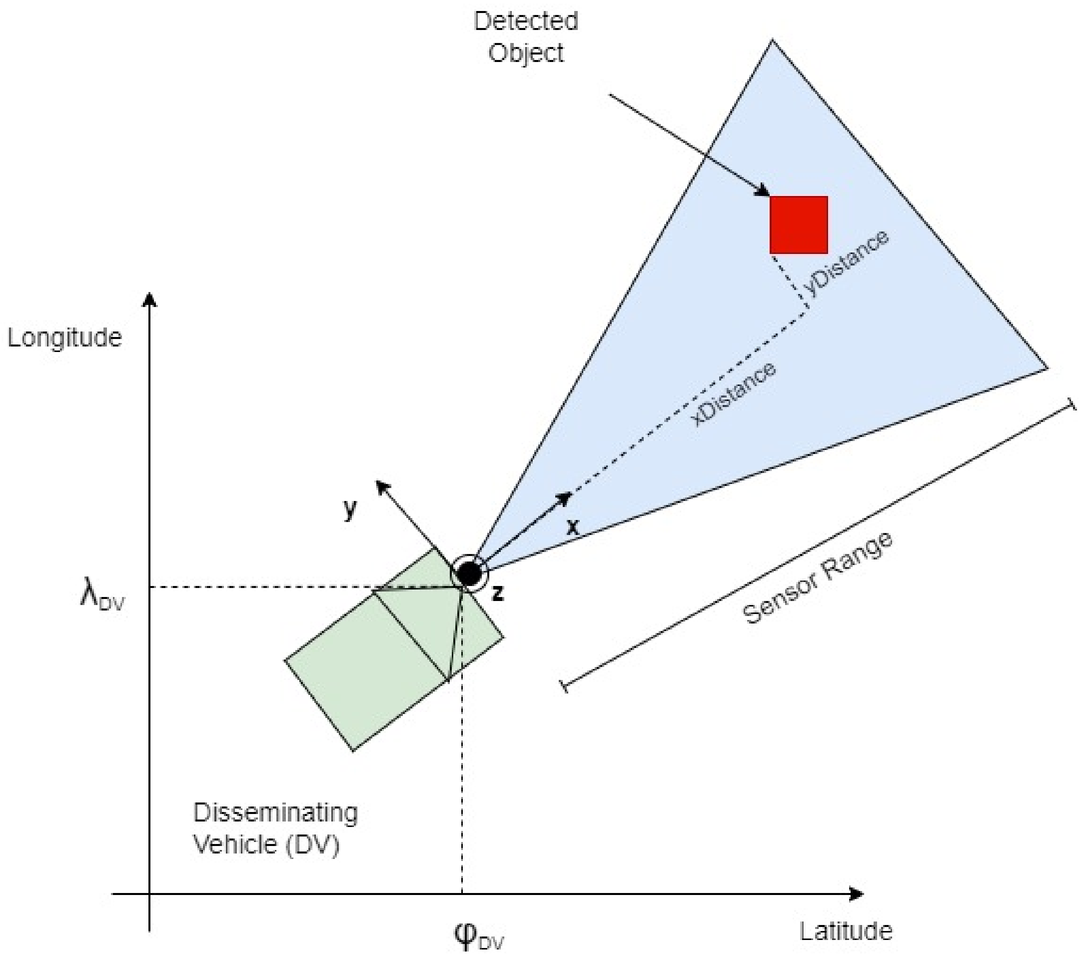

Figure 3.2: Coordinate System for the detected object for vehicle as disseminating ITS-S [41].

3.3.1 Station Data Container

The Station Data Container is an optional container which can be different based on the ITS-S type. It is needed to transform objects described in the CPM. In case of a vehicle as a transmitter, these information are vehicle dynamics such as Heading, Speed, Vehicle Orientation Angle, Pitch Angle, Roll Angle, Vehicle Height, Trailer Data, and etc. This is done to avoid problems in case the CAMs that are supposed to be sent parallel to the CPMs are not received. Because to interpret information inside the CPMs, information inside the CAMs are needed. In case of a RSU as a transmitter the Station Data container includes IntersectionReferenceID and RoadSegmentID, which are both optional. The StationDataContainer type is chosen based on the StationType set in the Management Container.

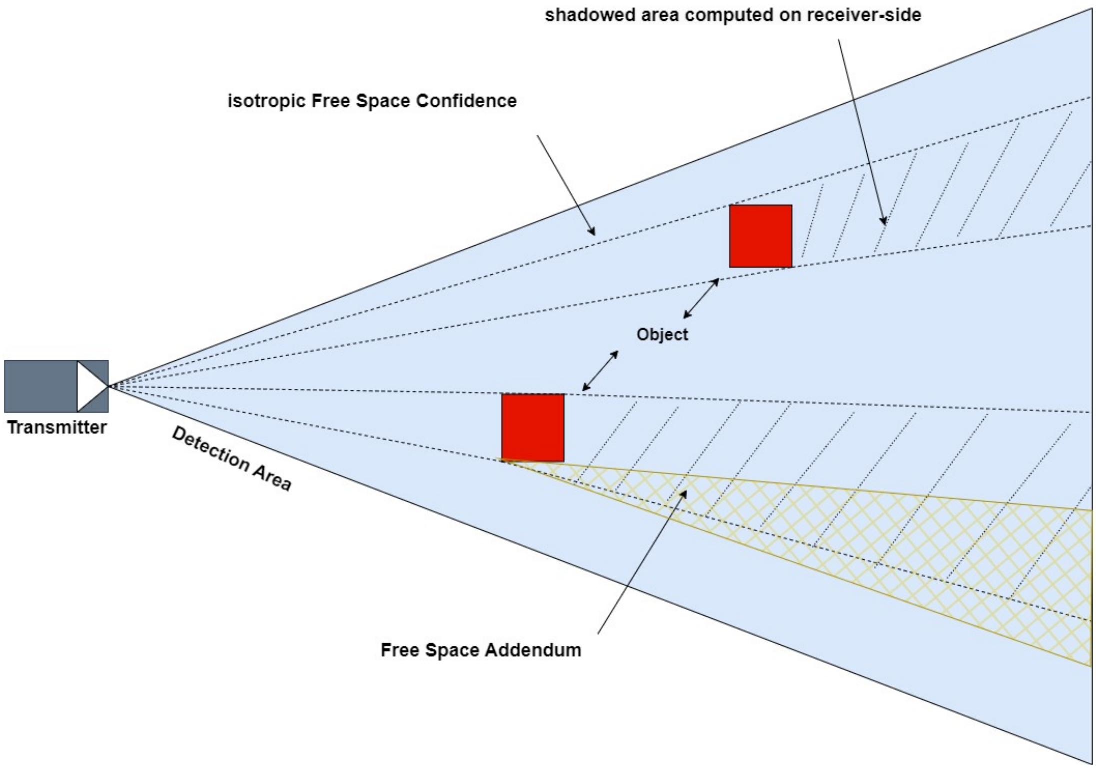

Figure 3.3: Computed Free Space from the perspective of a receiving ITS-S [41].

3.3.2 Sensor Information and Free Space Addendum Container

The Sensor Information Container is another optional container that includes information about the sensory setup of the transmitter to detect the surrounding. Two types of description is provided for this container: vehicleSensor DF, and stationSensor DF. The information inside these containers are consist of the mounting position of the sensor on the object which serves as the origin of the sensor specific coordinate system, as well as the range, horizontal and vertical opening angle, which will let the receiver determine how the transmitter is perceiving the surrounding. In the case of a RSU as a transmitter, alternative DFs are provided for cases where the perception area is created by combining several separate systems. Finally, the Sensor Information Container can also contain the FreeSpaceConfidence DE, which provides confirmed information about a detected free space. Figure 3.3 shows the scenario, where the blue area can be assumed to be free with an isotropic FreeSpaceConfidence; Then for each object detected by the transmitter, the receiving ITS-S should be able to compute the non-free and shadowed areas for which not enough data is available. Shadowed areas behind each object can be computed utilizing a ray-tracing approach. The transmitting ITS-S is also able to compute the expected shadowing model, and in cases the model does not apply or the computed free area does not cover the complete detection area, a FreeSpaceAddendumContainer DF can be added to the CPM, which is an optional container and provides confidence levels for certain areas within the DetectionArea. It is needed to be added only in case the confidence levels need to be altered with respect to the isotropic confidence provided in the SensorInfromationContainer. There may exist a list of sensorIds that links the sensor that provided the free space information.

3.3.3 Perceived Object Container

The the Perceived Object Container is another optional container inside the CPM which contains the information about the objects detected by the transmitter. Whenever an object is detected by a disseminating ITS-S according to the conditions mentioned before, a Perceived Object Container can be added to the CPM , which contains the dynamics of the detected object. Figure 3.2 depicts how the detected objects are described by providing at least the relative heading, distance and speed of the object with respect to a station's reference point in the x/y plane of the respective coordinate system. In addition, an ObjectID, and a time of measurement is also provided for each detected object. It should be noted that the last value is different than the GenerationDeltaTime that is stated in the management container. In fact, the GenerationDeltaTime corresponds to the latest point in time when the latest reference position is available on the transmitting side. This way the receiver is able to find out the age of the CPM by calculating its own GenerationDeltaTime upon receiving a CPM, and comparing the two values. The received Time of Measurement then needs to be added to the age of the CPM, to figure out the age of the detected object. In case of providing the fused object state information, the time of measurement corresponds to the point in time when the state space has been predicted. Other optional fields of a Perceived Object Container are Distance, Speed and Acceleration in three dimensions along with yaw angle, three dimensional description of the detected object, and the classification of each object.

Chapter 4

CPM Aggregation

4.1 MS-VAN3T framework Simulation Tool

The initial three chapters have presented a broad examination of various aspects related to ITS. A comprehensive depiction of the communication standards, with specific focus on the ETSI ITS-G5 Facilities layer, has been provided. This thesis work is primarily built upon two key components: the CP basic service and the MS-VAN3T vehicular network simulation framework.

Before implementing new features that involve cutting-edge technologies, the automotive industry has always devoted significant time to the testing phase. It has been previously stated that the success of most ITS applications depends on the rate of nodes in the vehicular network equipped with communication capabilities. Due to the collaborative nature of ITS applications, extensive fleets of connected vehicles are typically required for testing, resulting in various constraints, particularly in terms of economics and logistics. Consequently, it is crucial to model and simulate realistic environments for vehicular communications in order to develop and test new ITS applications. A major challenge in testing vehicular protocols within simulated scenarios is the necessity for bidirectional synchronization between network and road traffic simulations.

The foundation of this thesis lies in an open-source vehicular network simulation framework developed within the ns-3 simulator, which incorporates the SUMO (Simulation of Urban MObility) simulator to handle mobility aspects. Referred to as MS-VAN3T (Multi-Stack framework for VANET applications testing in ns-3), this framework is introduced in [43]. What sets this project apart from others is its consolidation of all access technology models offered in ns-3 into a single open-source repository. This unique integration enables seamless switching between different access technologies, thereby enhancing flexibility in application development. The access models supported by MS-VAN3T include:

. 802.11p for vehicle-to-vehicle (V2V) and vehicle-to-infrastructure (V2I) communications.
. LTE for vehicle-to-network (V2N) communications, known as LENA.
. C-V2X in transmission mode 4 for vehicle-to-vehicle (V2V) communications [44].

As outlined in the subsequent sections, the full integration of the ITSG5 stack, particularly for the 802.11p model, empowers MS-VAN3T to extend its simulation capabilities to the realm of emulation. This unique and pioneering attribute of MS-VAN3T enables the transmission and reception of packets that adhere to the ETSI standards, bridging the gap between the virtual simulation environment and the real world using a physical interface.

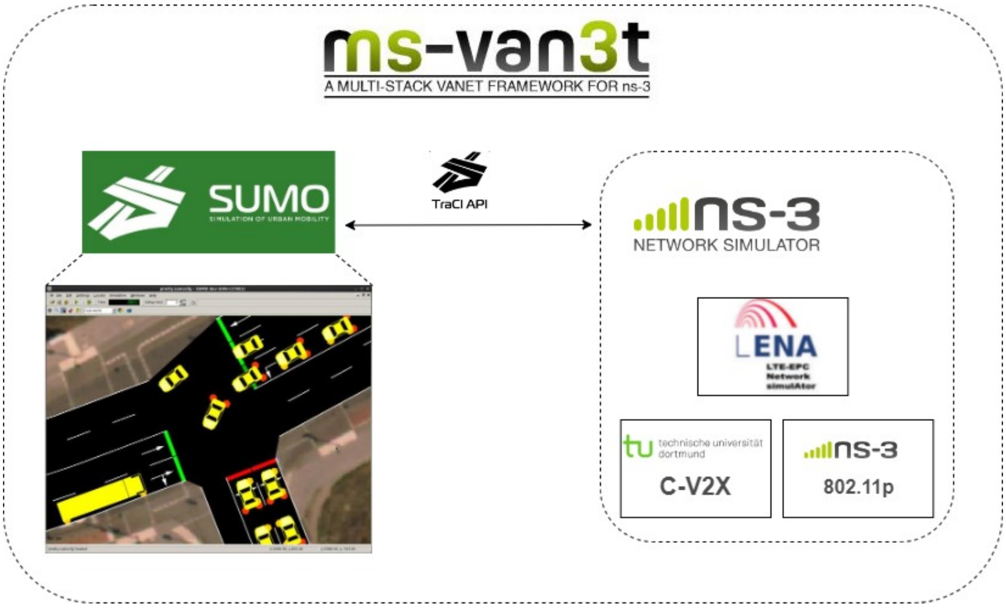

Figure 4.1: MS-VAN3T architecture [45].

As explained in [43], MS-VAN3T operates by connecting two simulators together:

- Firstly, there is SUMO (version 1.8.0 as of the time of writing), an open-source suite for traffic simulation. SUMO allows for the modeling of various modes of transportation, including road vehicles, public transport, and pedestrians [46]. It also facilitates interaction with simulation elements through the TraCI API [47]. Additionally, SUMO offers a user-friendly Graphical User Interface (GUI) that allows for interactive visualization of the ongoing simulation.
- Secondly, there is ns-3 (version 3.33 as of the time of writing), a discrete-event network simulator responsible for managing all the communications among

the entities involved in the simulation. ns-3 offers support for a real-time scheduler, enabling various "simulation-in-the-loop" scenarios for interacting with actual systems. This functionality allows users to transmit and receive packets generated by ns-3 on real network devices, while also serving as an interconnection framework to introduce link effects between virtual machines [48]. Unlike other simulation platforms that provide a unified graphical interface environment for all tasks, ns-3 follows a modular approach. It is designed as a collection of libraries that can be used in conjunction with each other and with external libraries. The simulator is primarily utilized on Linux systems, and users should expect to work with command line tools and utilize C++/Python software development tools.

- TraCI, which stands for Traffic Control Interface, enables the retrieval of simulated object values and facilitates real-time manipulation of their behavior. It utilizes a client/server architecture based on TCP to establish communication with SUMO. Additionally, TraCI provides a range of control commands that enable various operations, including executing simulation steps and terminating the connection.

In MS-VAN3T, every message exchanged adheres to the ITS-G5 standard and fulfills all the specifications outlined in Chapter 1, as well as the in-depth examination conducted in Chapters 2 and 3. The architectural representation of the framework is depicted in Figure 4.1.

4.2 MS-VAN3T Communication Models

As outlined in [43], MS-VAN3T incorporates V2I and V2N (vehicle-to-network) application models, where vehicles are set up to regularly broadcast CPMs/CAMs. The implementation of centralized scenarios involves the use of two distinct communication technology models. Depending on the chosen model, the resulting scenario will be categorized as either V2I or V2N. The communication models are:

- The utilization of the 802.11p standard is implemented through the WAVE model within ns-3. In this scenario, vehicles are equipped with OBUs and establish communication with a remote host located behind a RSU. Since the clients and server are in close proximity and share the same subnet, this communication can be classified as V2I.
- The LTE technology is implemented through LENA, which creates a conventional LTE network where vehicles function as User Equipments (UEs) connected to the eNodeB (eNB). In this case, the communication scenario

can be classified as V2N, as the UE is linked to a service provider that can potentially be located anywhere on the Internet.

On the other hand, As explained in [43] taking into account the V2V models, in order to offer a comprehensive range of scenarios, MS-VAN3T includes V2V (vehicle-to-vehicle) models too. In this specific setup, vehicles are programmed to broadcast CAMs/CPMs, which are then received by all vehicles within communication range, commonly referred to as neighbors. Upon receiving a CAM, each vehicle executes its own application logic. These V2V scenarios are supported by the following communication models:

- C-V2X mode 4, which involves vehicle-to-vehicle communication utilizing the PC5 interface via sideline, operating independently of an eNB.
- 802.11p is employed through the WAVE model. In contrast to the V2I scenario, in this case, CAMs, CPMs and DENMs are directly exchanged between vehicles without involving an RSU.

4.3 MS-VAN3T Applications Examples

In order to demonstrate the capabilities of the framework, MS-VAN3T includes two primary sample applications, as described in [43]. The first application, named Area Speed Advisory application, illustrates the V2I/V2N scenario, operating within a centralized client/server architecture. On the other hand, the second application, 'emergency vehicle alert', exemplifies the V2V scenario, functioning in a fully distributed manner.

Apart from the primary applications mentioned above, MS-VAN3T provides an emulation application that enables the transmission of CAMs and CPMs, generated by simulated vehicles, through a real network depending only on a physical interface.

4.3.1 Area speed advisory

The map utilized in this scenario, depicted in Figure 4.2, consists of two road crossings connected by a central two-way street. Positioned at the center of the map, the network access point (eNB for LTE and RSU for 802.11p) is configured to offer adequate coverage, ensuring connectivity for all vehicles operating within the simulated region.

The application concept involves dividing the map into two distinct areas, each with its own designated maximum speed limit. The first area, positioned around the network access point (referred to as the server within the application), is

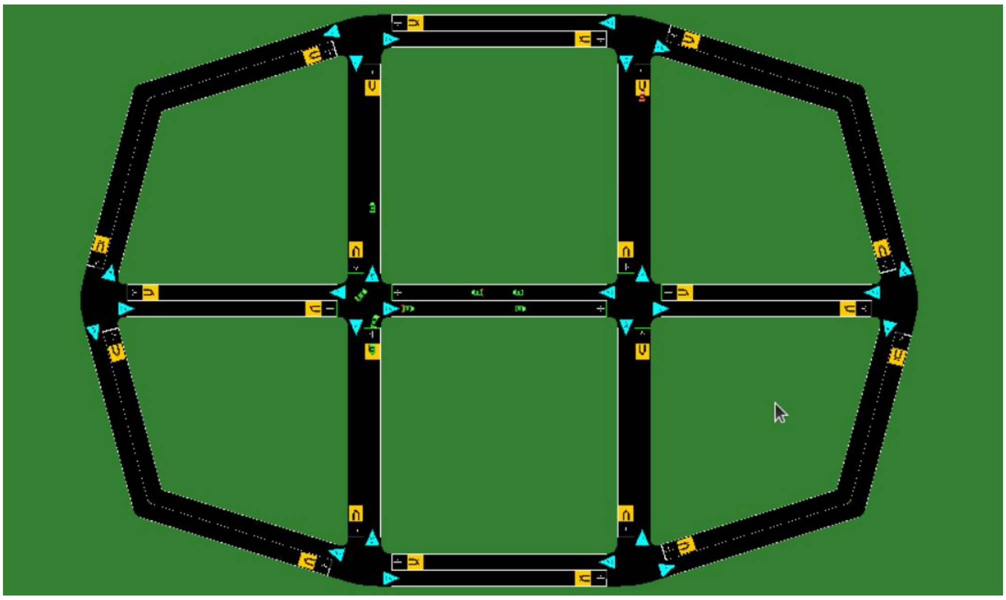

Figure 4.2: Area Speed Advisory map) [45].

located at the center of the map and has a maximum speed limit of 25 km/h. The second area encompasses the remaining portion of the simulated map and permits a maximum speed of up to 100 km/h. The exchange of CAMs and DENMs operates differently depending on the chosen access technology model, primarily due to the broadcasting limitations imposed by the LTE model.

In the case of the 802.11p model, vehicles are programmed to periodically transmit CAMs. Upon receiving a CAM, the server (i.e., RSU) promptly triggers the broadcast of a DENM to all vehicles (i.e., OBUs) within the low-speed area, providing a warning to drivers to reduce their speed. These DENMs are updated periodically, every second, unless the server has not received a CAM in the past five seconds. This indicates that no vehicles are currently present in the low-speed area, helping to reduce the channel load. If a vehicle within the low-speed area has not received a DENM message for one and a half seconds, it interprets this as having exited the area and is then permitted to increase its speed. The effective functioning of this mechanism is largely supported by the GN entity, which drops GBC packets (DENMs) when the vehicle is outside the specified low-speed area indicated in the GBC header. This prevents the application from receiving unnecessary DENM messages.

In contrast, the LTE model operates differently, as it employs a UDP/IPv4-based stack for message transmission, allowing only unicast messages. Consequently, there are some distinctions in the approach. In this case, the server closely monitors the vehicles' positions by reading the CAMs transmitted periodically by the vehicles.

If a vehicle enters an area with different speed restrictions, the server alerts the driver accordingly. The vehicles are configured to send CAM messages at regular intervals, which are received by the network access point and forwarded to the server. The server, equipped with knowledge of the boundaries between the two speed areas, analyzes the vehicle positions. When it detects a vehicle transitioning from one zone to another, it sends a DENM message, notifying the driver about the need to either reduce or potentially increase their speed. In this scenario, CAMs are unicast from the vehicles to the server, while the server generates and sends unicast DENMs to inform the vehicles about the speed area changes [43].

4.3.2 Emergency vehicle alert

In this particular application, the map utilized, depicted in Figure 4.9, comprises a circular road featuring two lanes in each direction. The vehicles are programmed with varying maximum speeds, ranging from 30 km/h to 60 km/h. In addition to the regular vehicles (referred to as passenger cars by ETSI [42]), this application introduces a new vehicle category known as Emergency Vehicles (EVs). These EVs are designed to simulate the behavior of ambulances, police cars, or even firefighting trucks. In the context of the emergency vehicle alert, the EVs are configured with a maximum speed of up to 75 km/h to replicate emergency situations.

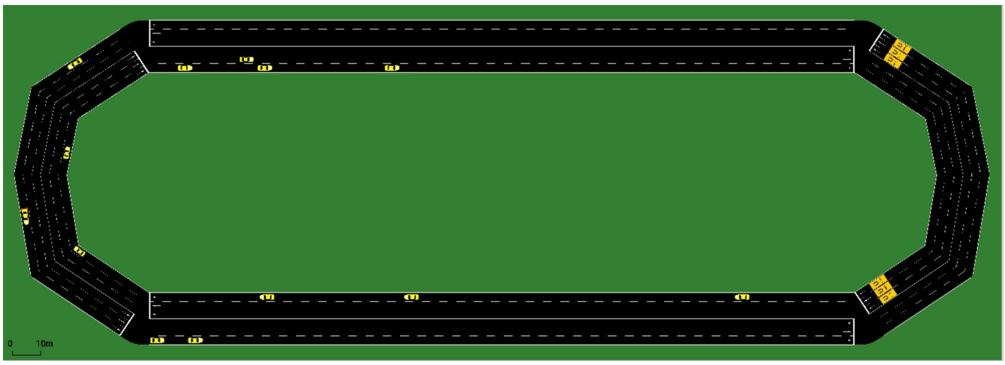

Figure 4.3: Emergency Vehicle Alert map [45].

Shifting the focus from mobility aspects to communication details, in this application, each vehicle is configured to periodically broadcast CAMs to all neighboring vehicles within communication range. When passenger cars receive a CAM from an emergency vehicle (identified by CAMs with the StationType Data Element set to specialVehicles), they assess the distance between themselves and the angle difference in their headings relative to the emergency vehicle. If both the heading angle difference and the distance fall below a predetermined threshold, the passenger car recognizes that the emergency vehicle is approaching. In such situations, if the passenger car is traveling on the same lane as the emergency vehicle, it will reduce its speed. Conversely, if the passenger car is on a different lane, it will promptly change lanes (even accelerating if necessary) as soon as it is safe to do so. As both access technology models (802.11p, C-V2X and NR-V2X) support broadcast communication, the application logic remains identical in both scenarios.

4.4 Algorithm description

In our model, the idea is to consider a cluster of ITS-Ss traversing the road as a Platoon, then aggregate the perception of each of these ITS-Ss altogether, to reach to a single aggregated and enhanced view of the surrounding. Afterwards, the leader of each platoon may send this data to Cloud. This way, a lot of computation power which was needed for each ITS-S to send their data to cloud and receive aggregated data will be saved.

Regarding the essence of this thesis project, the CPM aggregation strategy has been created within the previously mentioned MS-VAN3T framework. The receiveCPM function will be activated upon receiving a new CPM by each ITS-Ss separately. The Functionality is implemented within this function in the application. It should be noted that the focus of this thesis is on the effect of the aggregation of the incoming data from CPMs and already available data in the LDM of the ITS-Ss.

4.4.1 Translating Data

The CPMs are about the detected objects on the road, meaning it is assumed that the connected ITS-Ss that are able to communicate CPM, are also able to make themselves known by CAMs. The CPMs are received as an asn1cpp sequence (which is explained in Section 4.4.3), then the PerceivedObjectContainer inside the CPM parameters of each CPM will be checked to see if there is any object detected in the message to continue. If there is any, the logic will be ran for each of the objects.

To this end, inside each ITS-Ss that are equipped with the CP Service, an improved LDM called E-LDM is implemented, which is an LDM created from aggregation of data for the group of ITS-Ss and serves as a decentralized solution for aggregating information from incoming CPMs in order to better profit from the information shared by nearby vehicles. After receiving information about an object in CPM from transmitting ITS-S, this data needs to be translated to the receiver ITS-S point of view. Therefore, to calculate a given object's heading from receiver point of view, the heading value needs to be added to heading of the transmitter. By reference to the standard [41], the heading is measured with positive values considering the object orientation turning counter-clockwise starting from the x-direction, 3601 should be set if the value is unavailable.

Afterwards, by utilizing the functionalities provided inside TraCI-API to get the receiver's heading, and the heading value of the transmitter, the latitude and longitude of the transmitter inside the CPM, are transformed to x/y coordinate map of the receiver. Then by the help of the yawAngle and the relative distance of the object provided in CPM, the actual x/y translation of the object inside the receiver plane is calculated. In the same manner, the relative speed of the object provided inside the CPM, is transformed to x/y plane of the receiver.

4.4.2 Data Aggregation

Furthermore, the incoming information about objects inside CPMs need to be compared with the local data of the receiver already available inside its LDM. The reason is that, maybe this ITS-S has perceived the detected object earlier itself, or maybe it received information about the object earlier from other ITS-Ss. Similarly, the incoming information about the object needs also to be compared with the data inside the E-LDM.

To this end, there will be 4 different scenarios. First, if the object information is already available inside the Local data base or platoon data base, the incoming data needs to be aggregated considering all three values.Moreover, if there is no data in the enhanced database, then the aggregation needs to be done between the CPM value and the local database, On the other hand if there is no data in the local database , then the aggregation needs to be done between the CPM value and the enhanced database. Finally, if the object is not known previously to the ITS-Ss, then it is needed to be inserted inside the V-LDM, and also if not available in the E-LDM, it should be added there too. The flow of the processes for the CPM data in this application has been depicted in figure 4.4 .

In the cases where the object was already known to the receiver, an algorithm will check the perception time of the local data and the receiving CPM. In the case that the CPM data is older than our local data, it is discarded. On the other hand, if it is newer then the aggregation should be done. This is done to avoid removing already new data that might be more true to the reality of the object.

For aggregating the data, the logic used is Weight Average. It means the value inside CPM and local database is multiplied by their perception confidence, then will be added together and divided by the total confidence that is the sum of confidences. Then this new aggregated data with the original timestamp of the perception inside the CPM will be inserted inside the E-LDM. It should be noted that, the aggregation of position of the object is done inside the x/y plane of the receiver, but then this value is converted to latitude and longitude by the help of TraCIAPI

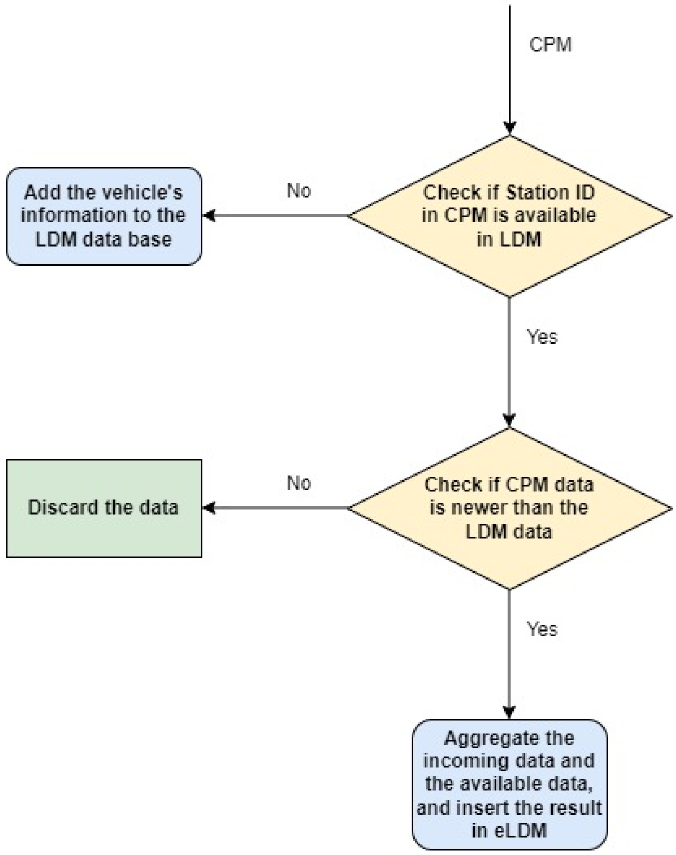

Figure 4.4: CPM inclusion decision Flow chart.

functions, and the latitude and longitude of the object is inserted inside the E-LDM.

4.4.3 ASN.1 and asn1cpp support

Before concluding the description of the developed CPS Aggregation model, it is important to mention that the fields present in CPMs have been appropriately configured using the Abstract Syntax Notation number One (ASN.1) notation [49]. ASN.1, which stands for Abstract Syntax Notation One, is a formal specification used for describing data transmitted via telecommunications protocols. It is independent of any specific language implementation or physical representation of the data, making it suitable for applications of varying complexity [50]. This notation encompasses fundamental data types such as integers (INTEGER), booleans (BOOLEAN), and bit strings (BIT STRING). Additionally, it enables the definition of composite types like structures (SEQUENCE), lists (SEQUENCE OF), and the ability to choose between different types (CHOICE).

The adoption of the asn1cpp tool is attributed to its ability to streamline the process of configuring message fields by providing a range of useful functions. For instance, the asn1cpp::MakeSeq(asn1cpp:TYPE descriptor t) function is utilized to declare a new asn1cpp sequence. Similarly, the asn1cpp::setField(Field,Value) function is employed to assign a value to a specific field. When dealing with an ASN.1 SEQUENCE OF field, the corresponding asn1cpp sequence needs to be declared first, after which the elements of the list can be set.

In this application asn1cpp is used to:

- get the sequence of data for a detected object of the CPM perceived object container with asn1cpp::getSeq
- to get variables of the CPM like numberOfPerceivedObjects with asn1cpp::getField

Chapter 5

Application Testing

In the preceding chapter, a comprehensive overview of simulation tools was presented, with a specific emphasis on the MS-VAN3T framework. Subsequently, the structure and functionalities of the developed CPM aggregation model were explained in detail. The next phase involves the validation of this work, which necessitates the creation of a new application using MS-VAN3T and testing the developed logic to figure out if there is any improvement in the awareness of the ITS-Ss included in the scenario. The framework's versatility enables the development and testing of a diverse range of application types, thereby facilitating the validation process.

5.1 CPM Aggregation Application

The map used for this application is the same as the Emergency vehicle alert Application; As described in chapter 4.3.2, each side of the road has two lanes. Then, there are 20 vehicle included, which Not all are able to disseminate CPMs/CAMs. The ones who can send CPMs/CAMs are named connected, and those without the ability to send information about them-self are called detected objects. It should be taken into account, the CPM is about these detected objects and not the connected objects. The connected objects will disseminate CPMs and the vehicle max speed is equal to 13.89. Moreover, each simulation has been ran for 200 seconds, and repeated 10 times for validation testing. It should be noted that in each simulation a new scenario has been chosen for the movement of each vehicle ITS-S. The map of the application is depicted in figure Figure 5.1.

The logic of the application operates when an approaching vehicle receives a CPM about a detected object on the road. The first seconds of the simulation do not include the use of the logic a lot, because the databases are empty and it takes a while till connected vehicle ITS-S make themselves know to each other by CAMs

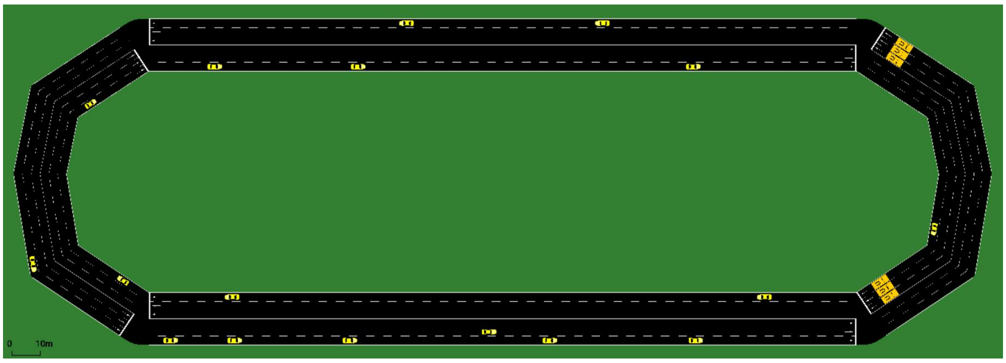

Figure 5.1: Test application map.

or CPMs arrive and fill the E-LDM. Just then, the moment a CPM is received by an approaching ITS-S vehicle, the aggregation logic will be ran.

5.2 Metrics

The main Key Performance Indicators (KPIs) considered to evaluate the improvement of the awareness in this thesis, is how much the whole awareness of the platoon improved with respect to the true values of the vehicles. Since as explained in previous chapter, we can request the ground truth values for dynamics of vehicles in the simulation from TraCIAPI and compare them with the values inside the E-LDM.These values can be:

- Position in x/y plane by command TraCIAPI::vehicle.getPosition (objectID), which then by command TraCIAPI::simulation.convertXYtoLonLat can be converted to latitude and longitude.
- Speed along x axis with command TraCIAPI::vehicle.getSpeed (objectID)
- Speed along y axis of the object by command TraCI::vehicle.getLateralSpeed(objectID)
- Heading of the object with command TraCIAPI::vehicle.getAngle (objectID)

Then, after running the application and if necessary aggregating and inserting data inside the E-LDM, 3 different sources of data has been considered, to showcase the improvement of the awareness with the help of presented aggregation method. In this work, the first criteria to evaluate has been the absolute difference between the true value of heading and position of the objects which has been taken from TraCIAPI as explained, the perceived and sent values of heading and position sent by the transmitter ITS-S in CPM. Secondly, the true heading and position value of the object has been compared with the heading and position values inside the receiving vehicle LDM, which may exist as the result of the object being perceived by the receiver earlier. And lastly, the heaging and position values of the object which may have been already inserted inside the Platoon LDM earlier are compared with the true values taken from TraCIAPI.

This is done to show how much the information inside the CPM, vehicle LDM and E-LDM are close the true values of the objects, and in case how the aggregation of the data inside these three source of data is helping to reach a better awareness of the object. In other words, how the CPM data are improving the knowledge of the ITS-S from surrounding.

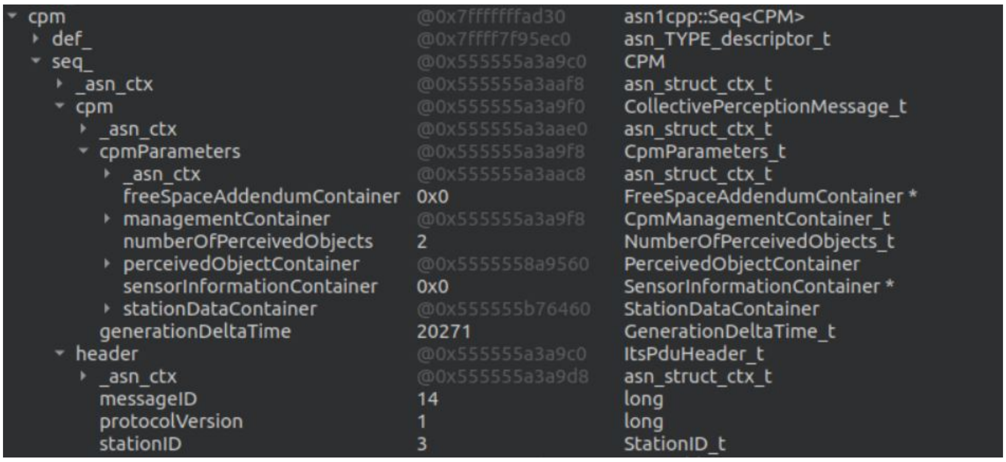

Figure 5.2: CPM smaple inside qtcreator.

The main information inside the CPM are shown in the Figure 5.2. For *station type*, identical data has been chosen.

5.3 Results

After running the simulations, the mean value of the whole data, the standard deviations, and the confidence intervals are shown in the tables 5.1 and 5.2. As can be seen the mean value for difference of the heading with the ground truth value in case of aggregating data and using E-LDM increases the accuracy of the information just received by the CPM. It goes the same in the Distance scenario. Therefore, CPMs are helping to improve the local v-LDM and subsequently the E-LDM. Our conclusion is that aggregating and sharing data inside a platoon helps a lot to improve the awareness of ITS-Ss. In the rest some snapshots of the outputs of the application and the information inside the LDM has been shown.

	CPM	V-LDM	E-LDM
Mean	7.8625	5158.5	145.38
Median	8.2296	2961.1	145.91
Standard Deviation	1.2828	6850.7	12.947
Confidence Intervals	[7.5724 8.1527]	[3608.8 6708.2]	[142.45 148.31]
int	[-0.2902 0.2902]	[-1549.7 1549.7]	[-2.9288 2.9288]
P95	9.5001	23567	165.53
P90	9.3391	15899	163.94

Table 5.1: Performances of the function in the case of evaluating the distance for only considering CPM, only only V-LDM, and only considering E-LDM scenarios

	CPM	V-LDM	E-LDM
Mean	7.6082	46.407	6.194
Median	7.0724	45.899	6.0618
Standard Deviation	2.8108	8.4937	1.9655
Confidence Intervals	[6.9724 8.2441]	[44.486 48.329]	[5.7494 6.6386]
int	[-0.6359 0.6359]	[-1.9214 1.9214]	[-0.44463 0.44463]
P95	14.0522	61.413	10.211
P90	11.7237	59.068	8.9784

Table 5.2: Performances of the function in the case of evaluating the heading for only considering CPM, only considering V-LDM, and only considering E-LDM scenarios

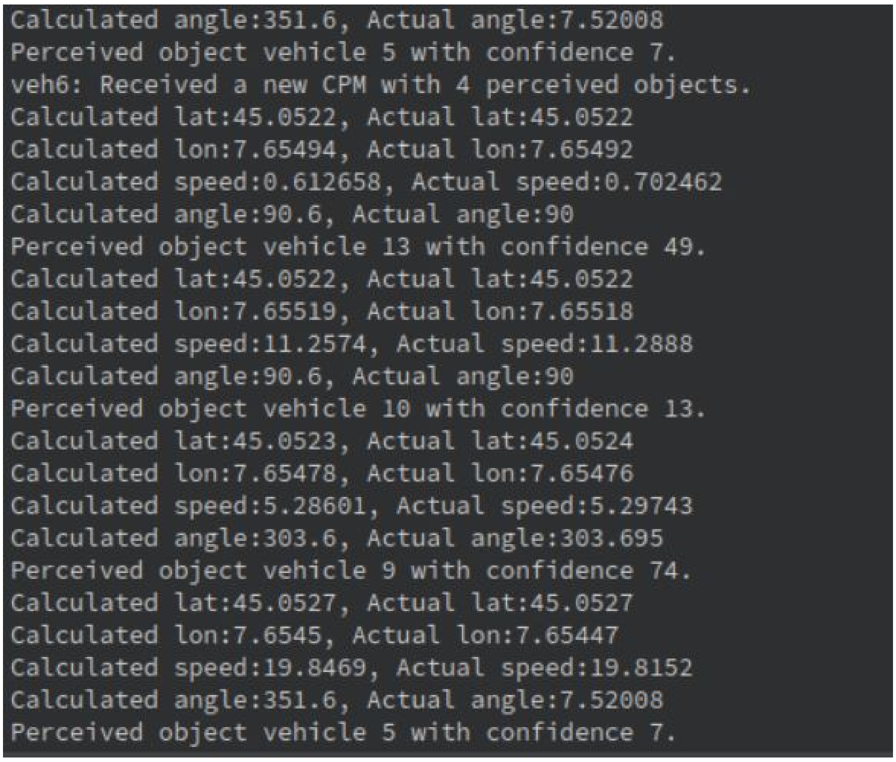

Figure 5.3: Snapshot of output of the application.

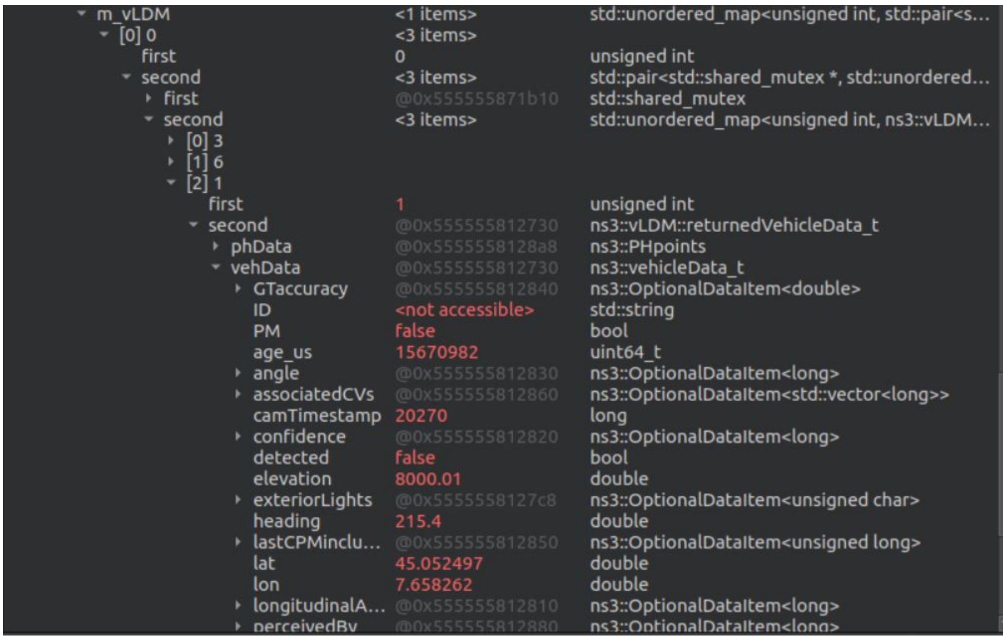

Figure 5.4: Snapshot of the LDM information inside the IDE.

Chapter 6

Conclusion

Intelligent Transport Systems (ITS) are becoming a reality, and progress is being made every day by automotive industries, government entities, and researchers worldwide to develop fully connected vehicles, which are the core of ITS. Over the past two decades, new technologies for vehicular communications have emerged, and efforts have been made to standardize them, enabling the coexistence of these technologies and facilitating the development of new ITS applications that can leverage their capabilities. This thesis begins by providing an overview of the current landscape of vehicular networks, briefly analyzing different access technologies and protocols in this context, and delving deeper into the ETSI ITS-G5 set of protocols.

Afterwards, Moving on to chapter 2, an in-depth examination is conducted on the standards that govern various facets of LDM. This analysis primarily concentrates on the role of LDM within ITS Facilities layer, and its applications and use cases. Additionally, the whole structure of the LDM, its APIs to interact with other layers in the communication stack has been explained.

One of the main features of the ITS-Ss is their ability to send and receive messages, to make themselves known to the other objects on the road, and to know about objects out of their sensing range. The later one can be accomplished by the usage of CPMs, which has been investigated in chapter 3. In the third chapter, an extensive analysis of the CPM concept provided by the standard has been mentioned. First its role , use cases and communication concept has been explained, and then the rules which makes CPMs performing better and the results of the standard performed simulations are mentioned. At the end the whole structure and rationals to fill CPM Containers are stated.

Delving into the primary goal of this thesis, we introduce the MS-VAN3T framework, which serves as the foundation for all the conducted research. As explained, MS-VAN3T encompasses an implementation of the ETSI ITS-G5 stack; the base of this thesis is a function of the open-source framework MS-VAN3T that helps in improvement of the awareness of objects on the road, in the scenarios where the transmission of the CPMs are enabled. In chapter 4, the core of the thesis, the way to utilize and interpret the incoming data and the algorithm used for the aggregation of this data and the local data inside Vehicle LDM (V-LDM) or P-LDM has been described.

In chapter 5, a detailed description is presented of an application that highlights the advantages of utilizing aggregation in receiving data. Based on the obtained results, it can be inferred that the functionality implemented inside the application, installed in a Vehicle ITS-Ss along a highway, optimizes traffic awareness by aggregating and taking advantage of the incoming CPMs and the local data such as V-LDM or P-LDM.

As for the future work, the logic utilized for the aggregation can get improved by using an a more complex approach such as Kalman Filter or AI/ML. Also, For the rules to not consider the incoming CPMs, another approach could be discarding really old data or those that are already reducing the confidence of the local data.

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