UNIVERSITÄT PADERBORN
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Simulation-based Performance Evaluation of Collective Perception Service with Cellular-V2X

Master's Thesis in Informatics

9. August 2022

Please cite as:
Chethan Lokesh Mariyaklla, "Simulation-based Performance Evaluation of Collective Perception Service with Cellular-V2X," Master's Thesis (Masterarbeit), Department of Computer Science, Paderborn University, Germany, August 2022.

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https://en.cs.uni-paderborn.de/cn

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Master's Thesis in Informatics

vorgelegt von

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geb. am 01. May 1992
in Karnataka, India

angefertigt in der Fachgruppe

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Abgabe der Arbeit:	**9. August 2022**

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(Chethan Lokesh Mariyaklla)
Paderborn, 9 August 2022

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Abstract

The Collective Perception (CP) service of V2X communication can be used to share the information about objects between vehicles. This sharing of information increases the vehicle's perception range beyond the onboard sensors. This service is under standardization in Europe and is considered an important feature for next-generation vehicles. Cellular-V2X (C-V2X) technology was introduced by Third Generation Partnership Project (3GPP) for Vehicle-to-Everything (V2X) applications using direct communication between devices on the sidelink interface. 3GPP introduces two modes of operation to send messages on the sidelink interface, managed and unmanaged mode. Vehicles autonomously select resources to send messages in unmanaged mode, whereas resources are configured by eNodeB (eNB)s in managed mode. In this thesis work, simulations are performed using Artery-C discrete event simulator, with the LTE-V2X protocol to independently measure the performance of the CP service in managed and unmanaged mode. For simulations, the InTAS traffic scenario is used to verify in conditions that closely depict the real-world traffic scenario. Different message generating models have been used to vary the periodicity of message generation, which directly influences the size of generated messages. The simulation results show that managed mode performance is better with all CPM generating models. Furthermore, the performance of CP is significantly affected with messages of variable size in the unmanaged mode, especially when the frequency of message generation is high. With the observed results, it can be concluded that vehicles operating in the coverage area of the base station can achieve better performance by operating in managed mode and also the performance of the unmanaged mode can be improved by reducing the frequency of the message generated without compromising the performance of CP service.

Chapter 1

Introduction

In recent years, extensive research has been carried out on the equipment of vehicles with different technologies to increase traffic safety and gradually progress towards having technologies that can be used to make the vehicle self-sufficient in all traffic conditions. V2X is one of those technologies in which communication is enabled between vehicles and also with other traffic participants, such as traffic signals and pedestrians, to share relevant information. Even the state-of-the-art sensors in the current automotive market have a perception range limited to the line of sight area. To support different features of Advanced Driver Assistance Systems (ADAS), such as collision detection when crossing the intersection or autonomously maneuvering between highway lanes; Vehicles require information beyond the line of sight perception range of mounted sensors. CP service [1] of the V2X technology enables vehicles to share the information collected from their sensors onboard with other vehicles. The receiving vehicle can fuse the information from Collective Perception Message (CPM) with the input provided by its sensors to increase its perception range beyond line of sight and to provide more information to help cross the intersection or other relevant applications of ADAS.

V2X communication can be enabled using wireless communication technologies such as Dedicated Short Range Communications (DSRC) in the US or ITS-G5 in Europe and cellular networks. DSRC [2] is operated with IEEE 802.11p standards in the 5.9 GHz frequency band, and the technology is mature for deployment [3]. 3GPP standardized direct device-to-device communications as a competing technology for DSRC that can operate without passing data through the base station of the cellular infrastructure. This direct communication can be used for V2X applications, and it also operates in the 5.9 GHz frequency bands [4]. Both technologies of vehicular communications are not interoperable [5]; therefore, it is necessary to understand the advantages and limitations of these technologies through research. This thesis is one such work to examine the performance of C-V2X in sharing information detected by sensors through the CP service.

Validation of V2X communication applications by developing the required equipment and deploying it in a real-world scenario is impractical considering both the financial costs and the safety of people [6]. However, it is necessary to test the technology in real-world scenarios to understand the different challenges faced when it is deployed for daily activities. Therefore, it is more suitable to validate it in a simulation scenario that depicts features close to the real world. In this thesis work, a discrete event simulator, Artery-C [7], coupled with InTAS [6], is used for simulations to measure the performance of the CP service. InTAS is a real-world traffic simulation scenario developed for the city of Ingolstadt.

In the following chapter, the fundamental concepts are discussed, along with the goals and key contributions of this thesis work. In chapter 3, the implementation of the CP service and the different message generating models created for the generation of CPM are presented in detail. In chapter 4, the simulation configuration for evaluating the CP service and the evaluation results are discussed. Finally, the thesis is concluded with Chapter 5.

Chapter 2

Fundamentals

THE aim of this chapter is to introduce the core concepts related to this thesis work. First, the description of C-V2X technology is discussed with its design of the physical layer and resource allocation strategies. Following C-V2X, the rules for the generation of messages using the CP service, together with the different containers added to the generated CPM are discussed in detail. Then, on the basis of this understanding, the related research works are reviewed, and finally, the chapter is concluded with the goals and key contributions of this thesis work.

2.1 Cellular V2X

3GPP released first device-to-device communication with Release 12, and this work was improved to incorporate it in Long Term Evolution (LTE) to develop the first standards for communication between vehicles in Release 14, and was improved in Release 15. In Releases 16 and 17, V2X communication based on 5G-New Radio was introduced. C-V2X uses 10 MHz or 20 MHz channel in the 5.9 GHz band [8]. The entity capable of sending and receiving messages is called User Equipment (UE). Direct communication between different UEs takes place through the PC5 or sidelink interface. This could be communication between two different vehicles, Vehicle-to-Vehicle (V2V), or vehicles and pedestrians, Vehicle-to-Pedestrian (V2P); also, vehicles communicating with the traffic infrastructure, such as traffic signals, termed Vehicle-to-Infrastructure (V2I) use the sidelink interface. Vehicles also communicate with base stations or eNBs to connect to the cloud for different infotainment services or connect to Intelligent Transport System (ITS) servers which are called Vehicle-to-Network (V2N) [9]. Communication with eNB is done through the conventional *Uu* interface [8]. V2X communication between different user equipment is shown in Figure 2.1. In the scope of this thesis work, simulations are performed only for vehicles that communicate with each other using the communication stack of LTE-V2X.

In C-V2X, vehicles can operate in two modes, managed and unmanaged. The primary difference between these two modes is the source of resource allocation in the sidelink interface for the transfer of V2X messages [8]. As shown in Figure 2.1, vehicles outside the coverage area of eNB operate in unmanaged mode, where vehicles autonomously select resources to send messages. On the contrary, vehicles in the coverage area of eNB can operate in managed mode, where vehicles can request eNB to configure the resource to send messages. It should be noted that vehicles can operate in unmanaged mode even when they are in the coverage area of eNB.

2.1.1 Physical layer

In LTE-V2X, 3GPP proposed a new physical layer design to enable V2X communication [8]. Single-carrier Frequency Division Multiple Access (SC-FDMA) is used for the modulation technique with channel bandwidths of 10 and 20 MHz. In the frequency domain, the channel is divided into different 180 kHz blocks called Resource Block

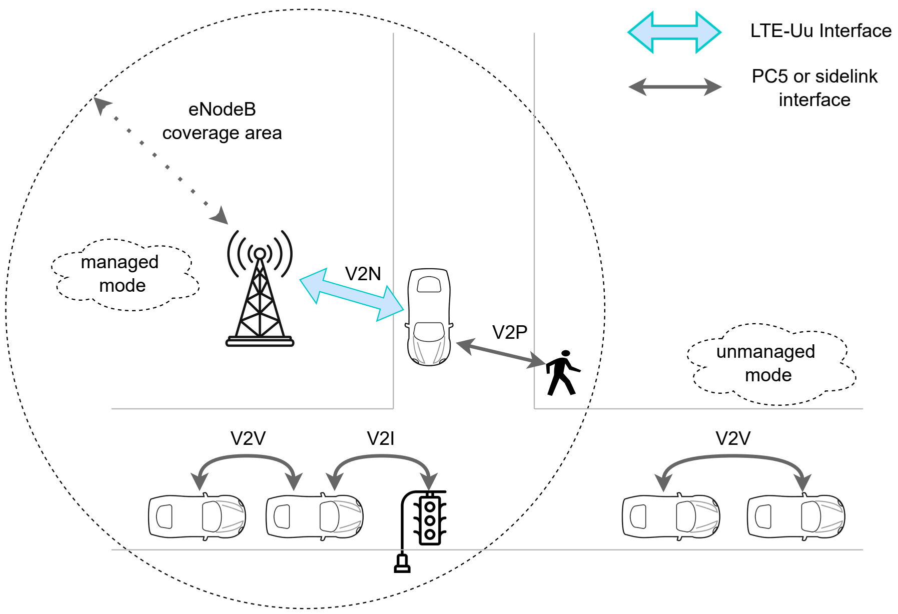


Figure 2.1 – Figure shows different V2X applications supported by C-V2X. The direct device to device communication for application like V2V, V2P and V2I is facilitated through PC5 or sidelink interface. V2N communication is enabled with *Uu* interface. If the UEs are present in the coverage area of eNB, then resource allocation can happen in managed mode and outside the coverage area, UEs operate in unmanaged mode.

(RB)s. Each RB is divided into 15kHz of 12 subcarriers. In the time domain, channels are divided into subframes of 1 ms. Each subframe is divided into 14 OFDM symbols, of which 9 are used to transmit data, 4 as a reference signal for demodulation and to negate the Doppler effect, and the remaining one as a guard signal for timing adjustments [8].As shown in Figure 2.2, the RBs in the same subframe are grouped to form a subchannel. These sub-channels are used to transfer data and control information. The number of RBs for a subchannel varies, and the configuration is carried out by individual vehicles or by eNB, depending on whether the vehicle is operating in unmanaged or managed mode. Each packet received in the physical layer can be transferred using multiple subchannels and is called Transport Block (TB) [8]. The number of subchannels used per TB is based on the size of the packet and also the total number of RBs present in a single subchannel.Sidelink Control Information (SCI) provides the information required to correctly decode the information present in TB and should be attached to each subframe of transferred TB; 2 RBs are required for each SCI. And each SCI contains information on the number of RBs occupied by TB, the modulation scheme used, the priority of the message, and information about Resource Reservation Interval (RRI). RRI is the periodic time interval that gives information about future subchannel reservations made to transfer the next TBs [8].

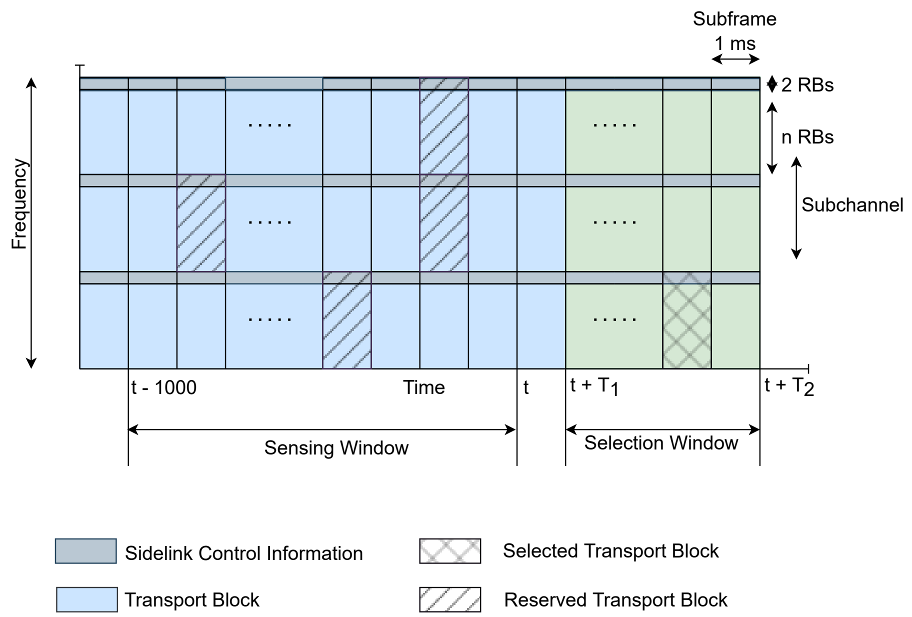


Figure 2.2 – Physical layer representation of LTE-V2X(adapted from [5])

2.1.2 Resource allocation

In this section, different resource allocation strategies used in managed and unmanaged modes to configure RBs in subframes to transfer V2X messages are discussed.

2.1.2.1 Managed mode

Vehicles operating in managed mode should be in the eNB coverage area. Whenever a V2X message has to be transferred, the vehicle uses the uplink interface to request eNB for resource configuration on the sidlelink interface [8]. As eNB receives regular updates from registered vehicles in its coverage area, it has information on the available resources for message transfer. Using this knowledge, based on the received request, eNB reserves the resources required to transfer messages. This configured resource reservation information is passed to the requesting vehicle through the downlink interface. The vehicle transfers the message to the RBs allocated in the side link interface. Resources can be configured in eNB based on two algorithms, dynamic or Semi-Persistent Scheduling (SPS), and the standards do not specify which algorithm should be used in implementations [8]. In the dynamic algorithm, every time the vehicle has to send a message, it will request eNB for the resources. This communication through the uplink/downlink interface to configure RBs creates considerable signaling overhead. If SPS is used for resource allocation, this signaling overhead can be reduced as eNB pre-allocates for a certain number of subsequent periodic transmissions [8].

2.1.2.2 Unmanaged mode

The information shared between vehicles through vehicular communication can be used to create applications that are critical for the safety of passengers and also to other traffic participants. Therefore, it is necessary for vehicles to be capable of sharing information regardless of its location. C-V2X standards propose the Sensing Based Semi-Persistent Scheduling (SB-SPS) algorithm in Release 14 to autonomously select resources without relying on eNB [8].

With SB-SPS [8], when the vehicle needs to send a message in unmanaged mode, it selects the resources in the available resource pool and reserves them for future subsequent transmissions with a periodic interval of RRI. The value of RRI is chosen from the predefined values ranging from 0 to 1000 ms. If the value of RRI is 0, then the resource is reserved for a single transmission. The number of subsequent transmissions depends on the randomly selected value of cResel. The range of cResel depends on the chosen value of RRI and is given in Table 2.1 [8]. After every transmission, the value of cResel is decremented by 1. And when the next message is generated, the vehicles reuse the available reservations to send the message. The vehicle initiates the selection of new resources if

1. cResel = 0 and the probability p is not in the range of $(1 - P_{RK})$, where P_{RK} is *Probability of resource keeping*.
2. The allocated size of the resources is smaller than the required resources.
3. the selected RRI do not satisfy the latency requirement of the new message received.

To select new resources, the vehicle senses the channel for 1000 ms, known as a sensing window. In Figure 2.2, the time t is when the selection of resources is triggered, and the selection window is given as *t to t-1000*. Based on the information received from other vehicles regarding the reserved resources and also on average Reference Signal Received Power (RSRP), the resources in the selection window are removed from the selection in the selection window. The selection window ranges from $t + T_1$ to $t + T_2$, where T_1 is the time required to select the resources and T_2 is configured according to the latency requirement of the V2X message. Among the available resources in the selection window, SB-SPS randomly chooses the resources required to send the message and reserves it for future subsequent transmissions for cResel times [8].

cResel value range	RRI
5,15	>=100ms
10,30	50ms
25,75	20ms

Table 2.1 – cResel values based on RRI [8]

2.1.2.3 Challenges with SB-SPS resource allocation

As discussed in the previous section, with SB-SPS the resources are allocated for a certain number of future transmissions, which can be called resource grants. These resource grants are broken if the new message size does not fit into the allocated resources or RRI does not meet the latency requirement. The authors in [5] present different challenges faced due to the variation in message sizes generated.

1. *Additional Re-selections*: If the generated messages are larger than that of the previous CPM message based on which resources were allocated, then the resource grants are broken, and new resources are allocated based on the increased message size. If this happens continuously, there is a continuous need for resource selections [5].

2. *Overlapping Selection Window*: If continuous re-selections are needed for all the vehicles in the neighborhood, sharing the channel. Then there is frequent overlap of the selection window. If two vehicles coincidently select the same RBs to transfer their messages, there will be a packet collision at the receiver. This situation is common in high-density traffic, where all vehicles exchange information with each other [5].

3. *Unutilized Reservations*: The reserved resources are not utilized due to two situations. First, when the resource grant is broken and new resources are allocated, as mentioned in point 1, the previously allocated resources are left unutilized. This condition is specific to the grant break because if reselection occurs because cResel is zero, then in SCI of the last message sent, the RRI is set to 0 indicating that the resource is available for reselection. The consequence of this broken grant scenario is that other vehicles are not informed of the free resources available for reselection [5]. In a high-density traffic situation, if there are regular grant breaks, then the resource pool gets exhausted without any available resources in the selection window either delaying the transfer of messages or dropping of packets. The second reason for unutilized resources is that during resource allocation the size of the message is larger, but, in the subsequent transfer the size of messages is smaller, then vehicle will use the same grant and transfer the generated message. In this case, the difference resource is left unused [5].

2.2 Collective perception

In V2X communication, cooperative awareness service has been already standardized where, vehicles share information about itself with other vehicles in its communication range. This message is called Cooperative Awareness Message (CAM) [10] in Europe and Basic Safety Message (BSM) [11] in the United States. However, considering traffic applications such as intersection crossings, it will be more beneficial to know, along with the information about this vehicle presence, the information it has gathered through its sensors. As introduced in Chapter 1, the CP service can be integrated to share sensor information. Standardization of this service is in process by European Telecommunications Standards Institute (ETSI), with its pre-standardized report TR 103 562 V2.1.1 [12] defining the rules for its generation and the message structure to use.

The information perceived by the sensors on board is fused together using different sensor fusion techniques to create Local Environmental Model (LEM), in which they track information from other vehicles in the sensor perception range. These objects tracked in LEM are used in the creation of CPM. Global Environmental Model

(GEM) is created by combining the information from the onboard sensors and that received from the CPM messages. Therefore, GEM will have more objects than LEM, resulting in an increase in its perception range. Also, the objects received from the V2X messages can also be used to validate the information that is tracked. As multiple vehicles send information about the same object in a short period of time, resulting in high data accuracy [13].

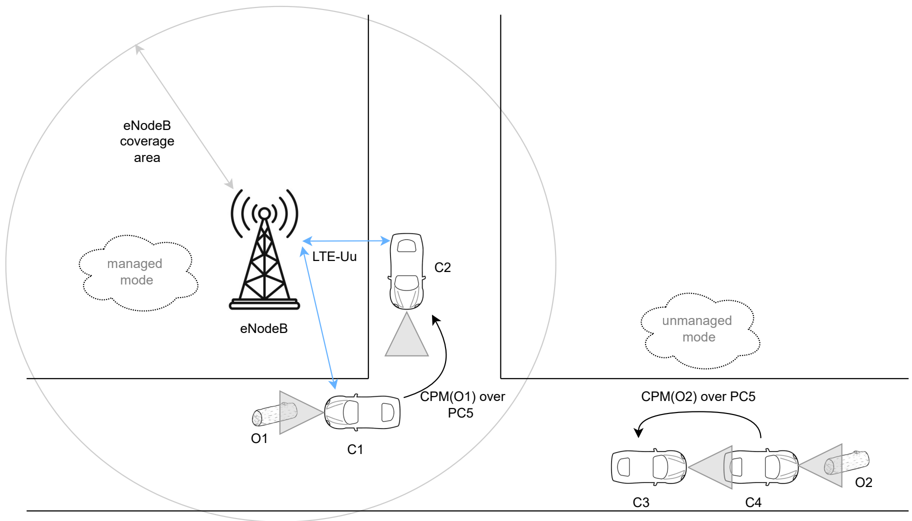


Figure 2.3 – Vehicles sharing CPM messages over PC5 interface. Car C1 sends CPM about detected obstacle O1 to C2 in managed mode and Car C4 to C3 about obstacle O2 in unmanaged mode

In Figure 2.3, cars C1 and C2 are in the coverage area of eNB and operate in managed mode. When obstacle O1 is detected by C1, it generates a CPM message containing O1 information and sends it to C2 over the sidelink interface. The resource to send this message is allocated by eNB on the LTE-Uu interface. In the case of C3 and C4, which are not in the coverage area of eNB, they will operate in an unmanaged mode. Therefore, C4 autonomously selects the resource to send the CPM message, which includes information about obstacle O2. Due to this sharing of information through CPM messages, C2 and C3 are aware of obstacles O1 and O2, respectively, although they are not in the perception range of their onboard sensors. In the following subsections, the generation rules and the content of the CPM message are presented.

2.2.1 CPM generation

The vehicle that generates the CPM message is termed *ego vehicle* in the scope of this thesis. The minimum time period between two CPM messages is 100 ms and the generation of CPM depends on perceived objects and its dynamics. If the dynamics of the object changes such that it would trigger a generation of CAM then that object is included in the perceived object list to send [12]. The generation is also dependent on the congestion control mechanism in the access layer. If there is a high channel load, the number of messages generated is reduced. The maximum time period between the two CPM messages is one second. Even if there are no perceived objects, CPM is sent with only sensor information [12].

2.2.2 CPM data structure

CPM message contains different containers that are assigned to transfer specific information, as shown in Figure 2.4 [12]. ITS-PDU header is common for all V2X messages and consists of a version of the message protocol, whether the message type is CAM, CPM, or Decentralized Environmental Notification Message (DENM) and also a unique identification number that recognizes the ego vehicle. With the ITS-PDU header, different CPM parameter containers such as station and management container, sensor information container, perceived object container, and finally free space addendum container. ITS-PDU header, management container, and, depending on the station type, the station data container is mandatory. Other containers such as sensor information, perceived objects, and free space addendum are optional to be added in the CPM messages sent.

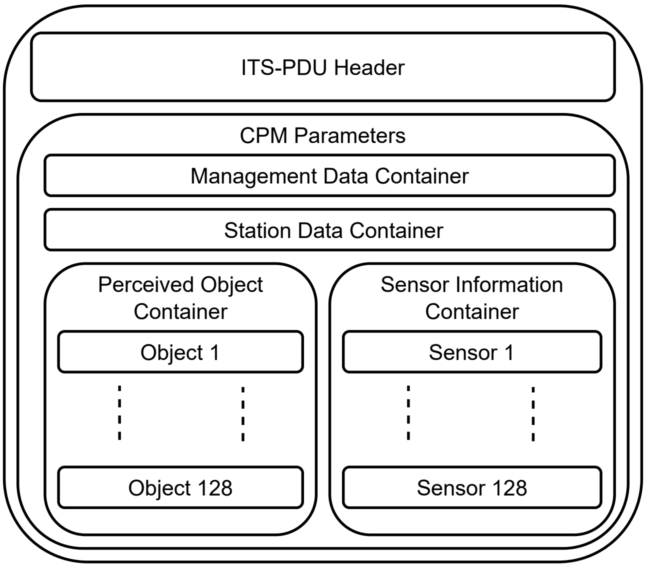


Figure 2.4 – CPM data structure (adopted from Figure 35, [12])

2.2.2.1 Station and management data container

The station and management data container [12] provides information regarding the ego vehicle. The management container is general and mandatory for all types of station-types, where the station data varies depending on the different types of station, mandatory for vehicles, and optional for Road Side Unit (RSU).

The station data container [12] added to vehicles gives information on vehicle dynamics. Dynamic information includes vehicle heading, speed, latitude, and longitude information. These dynamics of vehicles are helpful in mapping objects received with the perceived object container to the vehicle-centered coordinate system in the global environmental model. CAM messages with their high-frequency container provide this information about vehicle dynamics, which can therefore be considered redundant information. However, this information is necessary since CPM and CAM are not always sent together. So, the delay in receiving the information from CAM will affect the accuracy of processing and mapping the vehicle and objects received in GEM [12]. In addition, information is added, such as vehicle orientation angle, pitch angle, roll angle, vehicle height, along with basic dynamics information. This information will be helpful to know the accurate geometric dimensions of the ego vehicle. If a trailer is attached to the vehicle, the information of these trailers is also added in this container. The optional station data container for RSU will be included when it also transmits MAP messages to transmit information about intersections or road segments. In CPM information on the approximate position of the vehicle in a road segment or intersection related to the MAP message is added, together with the id of the road segment or intersection in CPM.

The management container [12] gives information on the type of station, whether it is any of the dynamic vehicle types such as passenger car, light truck, heavy truck, or stationary type such as RSU, along with the reference position relative to the global position. The reference position for vehicles is the center of the front side and for RSU the position on the road segment or intersection. Optionally, if the message is too large to hold in one CPM transfer, it is divided into different segments before it is transferred and the management container includes this information of the segments that are transferred. Segmented information consists of the number of segments with respect to the total number of segments and the total number of objects the CPM over all the segments. Each CPM message can be independently processed with the received objects; there is no compulsion that the received objects count should match the total number of objects information received.

2.2.2.2 Sensor data container

Sensor information data container [12] provides information on the sensors mounted on the station that sends CPM. These sensor information is sent once every second even though there are no objects detected in the perception area, as the receiver can be aware of the perception capability of the sender and increase its perception range. The sensor information included in the container is assigned an identification number, which is used in the perceived object container to map all objects detected with that particular sensor. Each sensor information in the container can be descriptive with details of the perception range and can differentiate between types of the sensors like RADAR, LIDAR, camera or even the object is detected with fusion of inputs from multiple sensors. Senors are mainly categorized into two, vehicle and stationary sensors. Vehicle sensors will include information on the mounting point with reference to the vehicle reference point given with the management container and information on the horizontal angles needed to calculate the sensor perception capabilities. The stationary sensors types are those mounted on RSU and include similar information to vehicle sensors.

2.2.2.3 Perceived object container

The perceived object container [12] contains the objects detected by the sensors, and is optional, added only if there is an object that needs to be transferred. Maximum of 255 objects can present in the container and each object detected will be assigned with identification number between 0 to 128, and 129th object detected will be assigned with 0. Along with object specific number, it will also contain id of sensor it is detected from. Each object entry will also include the measurement time that is used at the receiver to calculate its age. Euclidean distance of the object and speed with respect to ego vehicle is necessary for every object entry. 3D description information of the object can also be added.

The conditions for adding objects to the CPM sending object list according to ETSI standards as follow [12],

- Euclidean distance between the detected object and ego vehicle changes more than 4 $meters$.
- The absolute speed measured with respect to vehicle reference point between the detected object and the ego vehicle has more than 0.5 $meters/second$.
- Heading orientation between the object and the ego vehicle changes more than 4 $degrees$.
- A new object which was not included in the previous CPM is detected or a time period of 1 second has elapsed with previous inclusion and the object is still in the perception range of the vehicle.

- If the object is of type person or animal, if one object time difference between first and second inclusion is more than 500ms; all the objects of type animal and persons are added to the next CPM list.

2.3 Evaluation framework

In the following section, more details on the simulation tools used for this master thesis will be discussed.

2.3.1 Network simulation environment: Artery-C

Artery-C [7] is the OmNET++-based discrete event simulation framework developed for C-V2X. It is capable of simulating both up/down link and sidelink communication and can be used for Vehicle-to-Network and direct device communications such as Vehicle-to-Vehicle, Vehicle-to-Pedestrian, Vehicle-to-Infrastructure. Artery-C extends the control and user planes of simulte [14] for providing the sidelink interface for device-to-device communication. This extended simulte is added to Artery [15], a framework that implements facilities and the application layer; also, supporting features to develop different vehicular scenarios for developing V2X applications. For generating traffic scenarios, it is integrated with SUMO [16], a microscopic road traffic simulator. The framework supports managed and unmanaged modes along with dynamic switching between them based on whether the vehicles are in the area of coverage of eNB or not.

The architecture[1] of the Artery-C framework can be seen in Figure 2.5. The simulation framework has two major programs operated in parallel, OmNET++ and SUMO. OmNET++ contains two types of modules, global and local. Global modules are common to all simulation participants, including vehicles and eNB. Local modules are replicated independently in all vehicles or other components. TraCI manager is a global module that initiates SUMO and interacts with it using the TraCI connection to receive vehicle updates after each SUMO update step. SUMO scenario is loaded with the respective configuration files for road, traffic, and buildings. The facility layer includes different services that generate messages based on the application, such as CP service, CAM, and others. The middleware[2] module is responsible for maintaining the V2X services, passing messages from the facilities to the lower layer and vice versa. The services required for the simulation are configured with the *services.xml* file. The middleware also stores information on the ego vehicle dynamics updated from SUMO via Traci Manager.

[1] http://artery.v2x-research.eu/architecture/
[2] http://artery.v2x-research.eu/features/middleware/

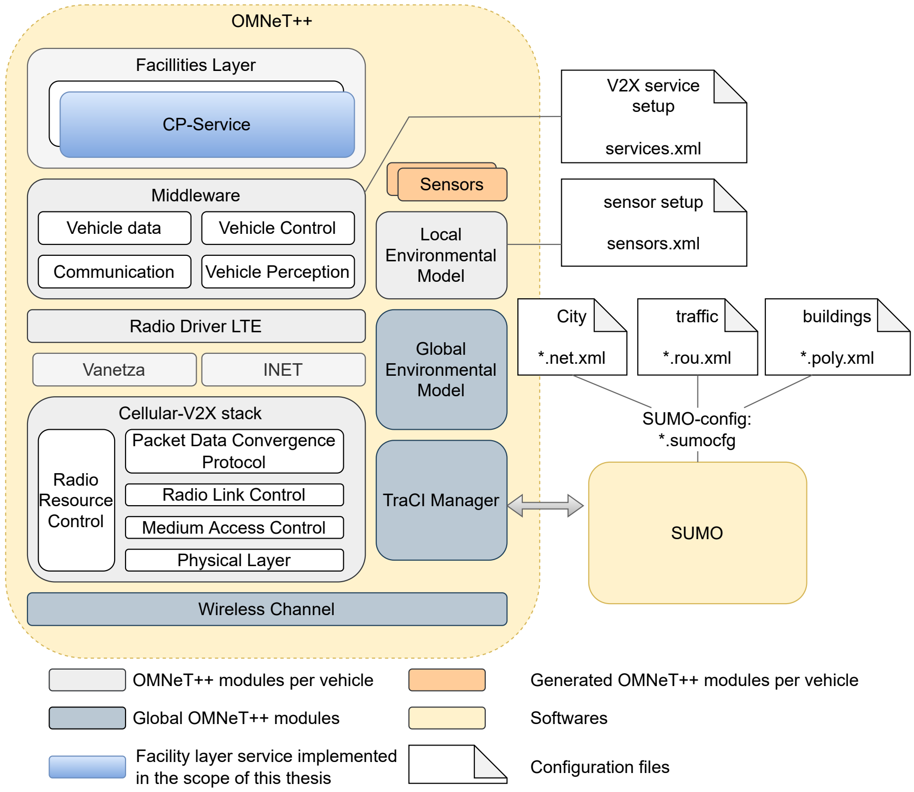


Figure 2.5 – Framework Architecture of Artery-C (adopted from architecture design of Artery)

The environmental[3] modules consist of local and global components. The global environmental model is common to all vehicles and tracks all vehicles, obstacles updated from SUMO. The local environmental model is specific to each vehicle and based on the sensor configuration given in *sensor.xml* the objects in the sensor perception are updated. During obstacle detection, at least one corner of the obstacle should be in the line of sight of the perception range of the ego vehicle sensor. The vanetza module implements different components of the ITS-G5 stack required to send V2X messages, and the radio driver LTE acts as an interface between the C-V2X stack and the upper layers. The C-V2X stack includes both the control plane and the user plane. The user plane includes the packet data convergence protocol, radio link control, medium access control, and the physical layer. The radio resource control represents the control plane.

Figure 2.6 – InTAS city map (adapted; [6], Figure 4)

2.3.2 Road traffic model: InTAS

InTAS [6] is a microscopic road traffic model developed using SUMO [16] for the city of Ingolstadt. In InTAS, an accurate mapping is done for all city roads according to categories of residential, public, and highway roads. Along with roads, buildings, bridges, and tunnels are also included, as they also influence communication. The traffic model is performed on the basis of real-world data collected from the concerned government office. Traffic lights also impact traffic movement; 20 traffic lights in this scenario run the same program as in real life, and the other traffic lights use the default setting. Public transport with different routes and stopping time at each bus stop is also incorporated into the traffic model [6]. Ingolstadt is an industrial city with the majority of people working with AUDI; therefore, vehicle movement is present around the clock, with maximum activity in morning 8:12 and afternoon 16:47 with 2,500 and 2,965 vehicles, respectively. Figure 2.6 shows the city map with the roads and buildings of the city of Ingolstadt mapped in InTAS [6].

2.4 Related work

Research on CP services has been carried out for more than a decade now. In 2012, the first concept of sharing sensor information via vehicular communication was proposed in [17]. Several research projects have been done in the research

[3] http://artery.v2x-research.eu/features/envmod/

community to evaluate the benefits of CP service on IEEE 802.11p. In [1], the authors discuss how the perception range of vehicles is increased with the use of CP service, especially when the Vehicle Penetration Rate (VPR) of V2X technology is low in the initial stages of market adaptation. The authors in [13] introduce different metrics to evaluate the benefits of the CP service in terms of increased environmental awareness and safety critical applications. They consider a highway scenario with an increasing penetration rate of vehicles with V2X enabled in the automotive market and analyze the effects on the communication channel, the awareness ratio and with the traffic safety. From the simulation results, they conclude that CPM increases the channel load, but provides a significant advantage with the increase awareness of the environment, with which anticipating the safety risk in traffic can be improved. Research work on the analysis of the generation of CPM is carried out in [18]–[22], to evaluate the policies given with the prestandardized technical report [12] and propose different techniques to reduce the network load through different redundancy mitigation techniques. These works support the ongoing standardization of CPM with ETSI [23].

The capabilities of the unmanaged mode to be used for C-V2X applications have been evaluated in different research works. The authors of [7] and [24] introduce the Artery-C and OpenCV2X simulation frameworks to evaluate C-V2X. In [7], the platooning application is evaluated when it is operated in managed mode and unmanaged mode, along with dynamic switching between modes. In [24], the authors discuss how the performance of the unmanaged mode deteriorates with an increase in the aperiodicity of the V2X messages generated. They consider grants broken if the messages are not received in the subsequent assigned transmission of SB-SPS with constant message sizes of 190 bytes.

The authors in [5] compare the unmanaged LTE-V2X mode with IEEE 802.11p using CAM generated with fixed and variable size; periodic and aperiodic traffic using different RRI values. The authors also present a detailed review of the different challenges discussed in Section 2.1.2.3 and conclude that with high variability in message size, the performance of the packet delivery ratio of the unmanaged mode is affected as traffic density increases. The authors of [25] evaluate the benefits of the CP service in an unmanaged mode using analytical models. They propose models for GEM, LEM discussed in section 2.2, for sensors used to detect objects, and also for metrics to evaluate the performance of CP service. Using these models, they verify on highway scenario with different traffic densities and conclude that unmanaged mode requires improvements to reliable use this as communication medium for safety critical applications.

2.5 Thesis goals and key contributions

From the literature review, we can conclude that little work has been done on the performance of CP service in the C-V2X environment with simulations. Although a good amount of work has been done on measuring the performance of CAM messages, the high variability of message size of the CP service, as it depends mainly on perceived objects, presents its own challenges. And, as discussed in Section 2.1.2, performance in unmanaged mode is highly affected by aperiodicity and varying message sizes. To the best of my knowledge, no research has been carried out to compare the performance of the CP service when vehicles are operating in managed and unmanaged mode.

In this thesis work, simulations are carried out independently for managed and unmanaged mode with CP service enabled in vehicles in a scenario close to real-world traffic. The goal is to evaluate and compare the performance of the CP service that generates messages of varying sizes; on the resource allocation strategies of managed mode and unmanaged mode. Furthermore, the messages are generated using periodic models to check if there is any improvement in the performance of the CP service.

The following are the key contributions of this thesis work,

1. The collective perception service will be implemented in the facilities layer of the simulation framework according to the ETSI standards [12].
2. Create different message generation models for CPMs .
3. Setting up the simulation framework Artery-C with InTAS for managed and unmanaged mode.
4. The periodicity and variation of the message size are analyzed for the generated CPM messages.
5. Analyze the performance of the CP service for both modes of C-V2X using relevant metrics.

Chapter 3

Collective perception with Artery-C

BASED on a general understanding of the fundamentals discussed in the previous chapter about the CP service and its message content. This chapter presents details of the implementation of the generation of CPM and its containers with relevant flow charts in the Artery-C network simulator. Following the details of the implementation, different messaging models created by altering the CPM generation conditions and its features are presented.

3.1 Collective perception service implementation

The CP service is implemented based on ETSI TR 103 562 V2.1.1 [12]. The service is enabled in the middleware by modifying the services.xml configuration file as shown in Figure 2.5. Services in the facilities layer have access to different middleware modules to access information regarding its position in the simulation, configured sensors, and objects perceived in the simulation. This information is required to create the respective containers. In the following subsections, details on the implementation and deviations from the standards [12] are discussed to adapt to the Artery-C simulator.

3.1.1 Generating CPM header files

As described in Section 2.2, the content that must be added in each CPM is predefined by the standards. This predefined content is accessible from Annex A of TR 103 562 V2.1.1t[12] in Abstract Syntax Notation.1 (ASN.1) format. This ASN.1 should be converted to the C++ format code to be used for the implementation of different containers of CP in the Artery-C framework. The CPM ASN.1 file, together with the other ASN.1 files on which CPM depends, such as the ITS-PDU header, are complied together using the *asn1c* compiler[4]. The compiler produces the output of the C++ source and header files, which are added to the vanetza module of the framework.

3.1.2 CPM generation steps

The conditions to trigger the message generation in the CP service vary depending on the message generation model used. In this thesis work, messages are generated based on three models; ETSI, ETSI-K, and Fixed Xms. Where X in Fixed Xms is the value of configured periodic interval for generating messages is chosen between 100ms, 300ms, or 500ms. On the basis of the model used, the number of CPMs generated per second varies. The message generation models, along with their respective conditions to trigger the generation of CPM, are described in Section 3.2. All services in the Facilities layer, including the CP service, will be registered with the middleware service (Figure 2.5). The middleware invokes each registered service to generate the respective service messages based on the update interval. The update interval is chosen as 100ms, as the minimum time of CPM generation is 100 ms. The framework is designed to add a small random jitter to this update interval, to prevent all registered services from generating messages at the same time [15]. The flow chart showing the high-level steps of CPM generation is shown in Figure 3.1. The vehicle which generates the CPM message is called an ego vehicle in the scope of this thesis. After the check for necessary conditions for the particular model is satisfied, CPM generation is invoked. Following the trigger, sensor information is added in Sensor Information Container (SIC), if the container was not added in any CPM in the last second and the selected perceived objects are added in Perceived Object Container (POC). The creation of SIC and POC is explained in detail in Sections 3.1.4 and 3.1.3, respectively.

The CPM is created and passed to lower layers to send, only if there is any information present in either sensor or perceived objects container. But in this implementation, an expectation is added to send CPM without sensor or perceived container if CP service is configured to send CPM with Fixed Xms. The reason for this deviation is to maintain the periodicity of generation with the fixed-interval model. Lastly, Station and Management Container is added (Section 3.1.5). In case of Fixed Xms, if there are no SIC and POC, then the CPM message will have only SMC. As discussed in section 2.2.2.1, with SMC information of the ego vehicle is transferred which is similar to the CAM messages. After adding all relevant containers, the size of the CPM is verified and reduced to maintain the generated size of CPM with a maximum limit of 1100 bytes [12](Section 3.1.6). The prepared CPM message is sent to the lower layers and the sent time is also stored to calculate the time elapsed for the next CPM generation.

[4]https://www.asn1c.com/

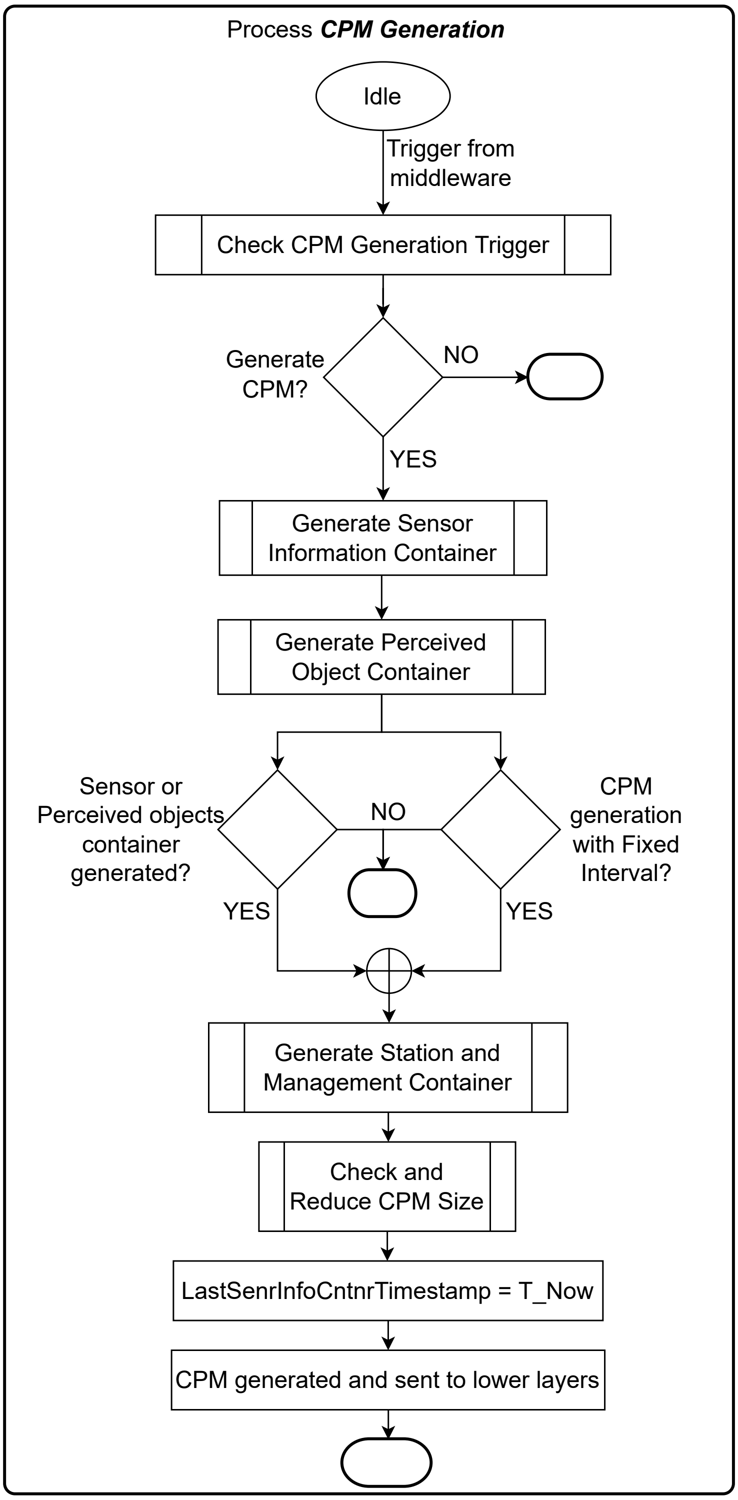


Figure 3.1 – Flow chart for CPM Generation (adapted according to thesis implementation; [12])

3.1.3 Generating perceived object container

The Perceived Object Container includes information on all objects perceived by the sensors of the ego vehicle. Based on sensor data, the ego vehicle stores the information of all identified objects in LEM. In simulation, for an object to be considered as perceived by the sensor, any corner of the vehicle should be in the configured perception range of the sensor. Whenever the CPM generation is activated, the CP service in the facility layer requests LEM for the updated object list. The flow chart for the inclusion of objects is shown in Figure 3.2. For the scope of this thesis only vehicles that are perceived through sensors are considered objects, and hence no information of object-type person or animals will be considered in the perceived object container.

Each object received from LEM is processed separately to verify that it is appropriate to add it to the list of sending objects for the current iteration of CPM. Not all objects perceived in each iteration of CPM must be added. If an object has already been sent in a previous CPM iteration, it will be tracked separately as tracked objects in internal CP service memory. In the case that the perceived object is not present in the tracked object list, this object is considered a newly detected object, and then the object information is updated in both tracked object lists and the send object list. In case of a tracked object, if it was included in the CPM that was sent before 1 second, then it is added to the send object list. If the time difference between the current and previous inclusion is less than 1 second, the object's dynamics will be tested. The object is added if the absolute difference between the speed of the object and the ego vehicle is greater than $0.5 m/s$ or the absolute difference between the direction orientation of the tracked object and the ego vehicle is greater than $4°$ or the Euclidean distance between the tracked object and the ego vehicle is greater than $4 meters$. After processing all objects, each object in the sender list is encoded according to ASN.1 encoding, and the perceived object container is created and added to CPM. The tracked object list is updated with the values of the new sent object list. The tracked objects have a lifetime of 1.1 seconds, that is, if the objects are no longer in the perception range of the ego vehicle the object is discarded from tracking after 1.1 seconds. If there are no perceived objects, the container of perceived objects is not included in CPM.

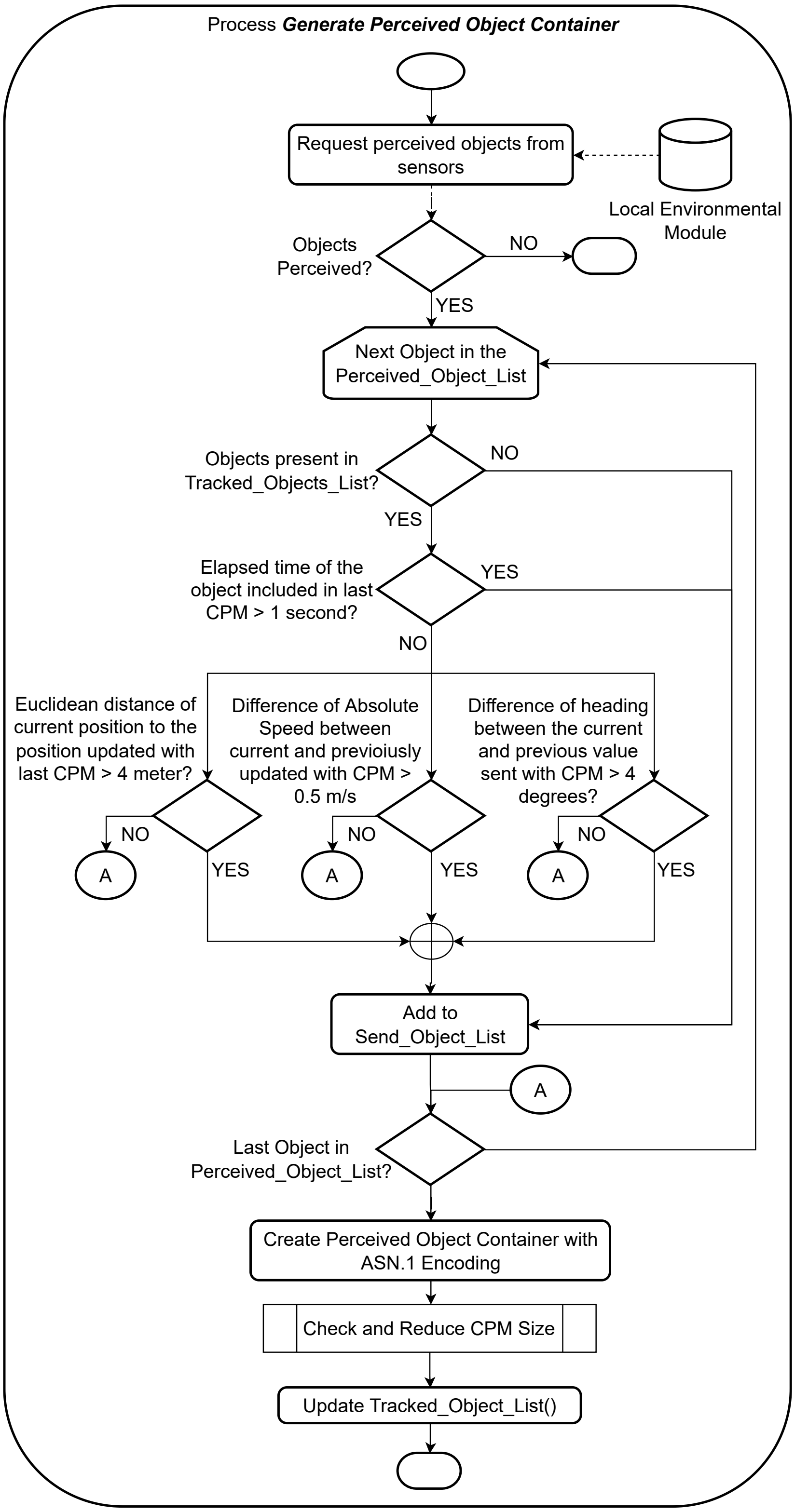


Figure 3.2 – Flow chart for creating Perceived Objects Container (adapted according to thesis implementation; [12])

3.1.4 Generating sensor information container

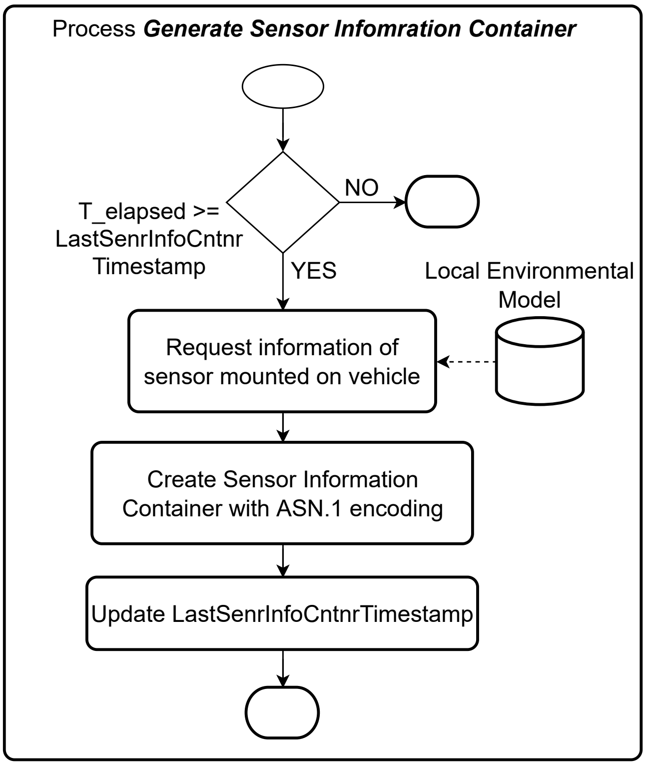


Figure 3.3 – Flow chart for generating sensor information container (adapted according to thesis implementation; [12])

The sensor information in the Artery-C framework is configured with sensor.xml files as shown in the architecture diagram 2.5. All configured sensors for each vehicle are stored in Local Environmental Model. The steps to add the sensor information container is shown in figure 3.3. When the time elapsed between the current generation time of CPM and the last CPM message with the sensor information container is equal to or greater than one second, the request is made to Local Environmental Model to collect information of mounted sensors. With the collected information, the sensor information container is created according to the ASN.1 encoding and added to the generated CPM.

3.1.5 Generating station and management container

The vehicle data provider is a sub-module of the middleware module (Figure 2.5). Vehicular movements in SUMO are updated with the help of the TraCI manager module. This information is essential for creating the station and the management container, and Figure 3.4 shows the steps and interaction with the modules to add

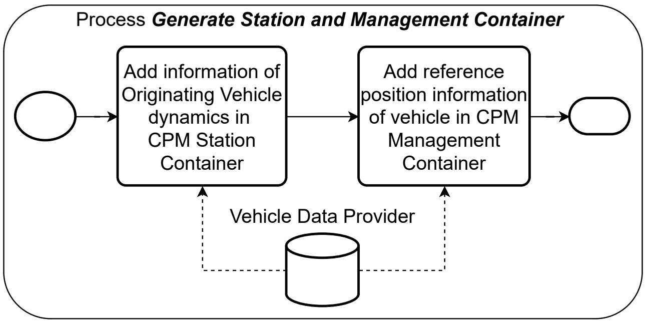


Figure 3.4 – Flow chart for generating station and management Container (adapted according to thesis implementation; [12])

the container. With all the conditions satisfied for the generation of the CPM as discussed in Section 3.1.2, the final container to add to the CPM message is the station and the management container. In the scope of this thesis, only dynamic vehicles are used for simulations, hence in the station container information of speed and heading is added with updated information from the Vehicular Data Provider. Similarly, reference position information is added to the management container.

3.1.6 Check and reduce CPM size

ETSI standards [12] specify segmenting and sending multiple CPM messages if the message size is greater than the maximum limit of 1100 bytes. In the scope of this thesis work, if the object size is increased more than the maximum limit, then objects are randomly removed from the sending object list and a new perceived object container is created for the CPM. These steps are followed until the CPM size is less than the maximum limit, as shown in the flow chart diagram 3.5.

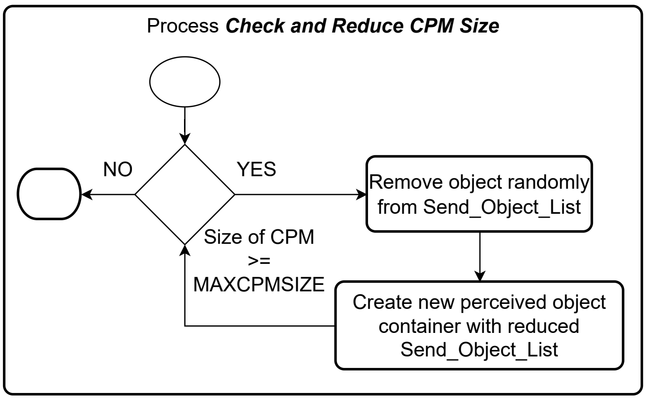


Figure 3.5 – Flow chart for reducing CPM size (adapted according to thesis implementation; [12])

3.2 Collective perception message generating models

Collective perception used to share information on perceived objects with high traffic density can increase channel load, affecting the performance of C-V2X resource allocation. Therefore, different message generation models are evaluated to vary the number of messages generated per second, which coincides directly with the number of objects added in the perceived object container, and also with the successful transfer of messages over the wireless channel. In this section, different models used to generate collective perception messages are discussed. Table 3.1 lists the different models used.

Model	Message generation characteristics
ETSI	According to ETSI standards [12]
ETSI-K	According to ETSI standards [12] + ego vehicle kinematics
Fixed 100ms	With periodic time interval of 100ms
Fixed 300ms	With periodic time interval of 300ms
Fixed 500ms	With periodic time interval of 500ms

Table 3.1 – CPM generating models

CPM generated with different models has a significant impact on how resources are used in the channel. The message size of all models depends on the number of objects included in the perceived object container of the CPM and whether the sensor container is included or not based on the conditions discussed in Sections 3.1.3 and 3.1.4 respectively. The minimum and maximum time between two CPM is configured as $T\_GenCpmMin$ and $T\_GenCpmMax$ with values of 100 ms and 1 $second$. All the modes should adhere to this restriction. The time interval between the current trigger time to the time when last message was set is termed as $T_{elapsed}$, which is compared with the minimum and maximum time bounds to decide whether to generate CPM or not.

If the generation of the CPMs is configured to generate in fixed periodic interval that is for *Model Fixed*, then CPM are generated periodically irrespective of the perceived objects. Based on model of generation configured, the $T_{elapsed}$ is compared with $T\_GenCpmMin$ or the configured fixed interval time (100ms/300ms/500ms). If not configured with a fixed interval, the generation of the CPM may or may not depend on the generation model used. If CPM generation is also based on the dynamics of the ego vehicle, then information related to vehicle dynamics is obtained from the vehicle data provider module (Figure 2.5). The dynamics considered includes speed, heading, and position and is constantly compared to its values when the previous CPM was generated. In case the dynamics are low; CPMs are generated once in 1 second. In the case of a high dynamic scenario, the CPM

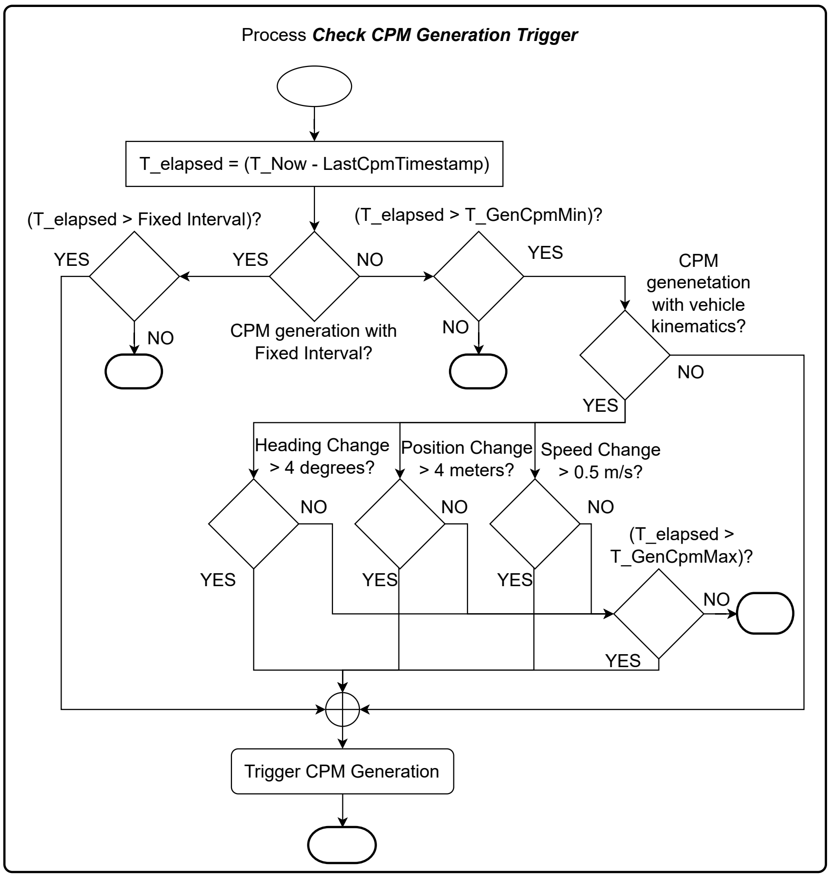


Figure 3.6 – Flow chart for CPM Generation trigger based on generation models

generation conditions are the same as that of CAM. That is, CPMs are generated if there is a change of position of more than 4 $meters$ or if the heading changes more than 4° or the speed of the vehicle changes more than 0.5 m/s. If the generation model follows the standard ETSI rules, then CPM generation is triggered every time the elapsed time is crossed $T\_GenCpmMin$.

With fixed models generating messages in different time intervals are used to analyze with varying message size which periodic interval gives better performance. The periodic time interval of 100ms is the minimum time interval between two CPM generated as specified in the standards [12], and this model is expected to create more stress on the channel due to frequent grant breaks. The time interval of 300ms and 500ms is considered, as the frequency of the messages is generated more in the range of 300 to 500 ms. This helps in analyzing the time interval, which is beneficial for maintaining the quality of the CP service and reducing the load on the channel by sending fewer messages.

Chapter 4

Evaluation

In this chapter, the description of the simulation environment used to perform experiments, using different models of CPM generation is given. Based on the results, the generated CPM messages are analyzed to check how frequently the messages are generated and its size according to the model used. Lastly, a detailed discussion of the simulation results with performance metrics of the CP service has been made.

4.1 Simulation setup

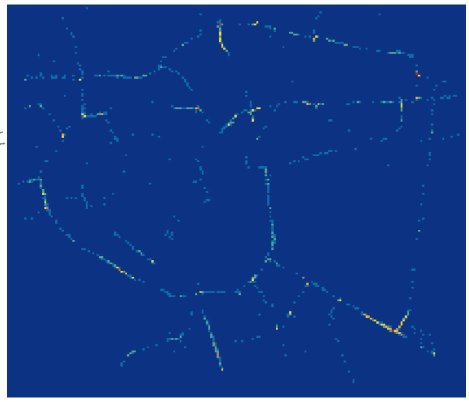
Simulations are performed using the Artery-C framework using LTE-V2X as the C-V2X stack. The different configured parameters are summarized in Table 4.1. For resource allocation using SB-SPS in unmanaged mode, the value of RRI is fixed to 100 ms. As explained in 2.1.2.2, the RRI value determines the time interval between the reserved resources for future transmissions. The value is fixed to 100 ms since the minimum time interval between the two CPM generation is 100 ms. In managed mode, resource allocation is done using the dynamic scheduling algorithm.

Simulations are performed using the reduced InTAS scenario. The original dimension of the InTAS scenario is 13574.18 x 11092.15 meters. This dimension includes the road network between the surrounding villages and the city of Ingolstadt [6]. As managed mode requires the addition of eNBs, the scenario is reduced to consider only the road network with more traffic density to limit the number of eNBs used. A total of 11 eNBs are added to the reduced map and all are connected to the X2 interface with the full mesh topology as instructed in the simulte[5]. The reduced InTAS scenario with the positions of eNB is shown in Figure 4.1a. The simulation area was reduced using the *netedit* tool[6] of SUMO, the reduced dimensions are 4303.58

[5] https://simulte.com/tutorial-x2.html
[6] https://sumo.dlr.de/docs/Netedit/index.html

x 4159.18 meters. Traffic routes of all vehicles are reduced using the *cutroutes.py*[7] script of SUMO. The traffic density with 1000 vehicles in the scenario is shown with the heat map given in Figures 4.1b.

(a)



(b)

Figure 4.1 – Figures with reduced Ingolstadt map; (a) with positions of eNodeBs, (b) with traffic density represented in colored pixels; Number of vehicles: 0 (no pixel), 1-2 (light blue), 2-4 (yellow), 5-6 (orange)

Each vehicle running in the simulations is equipped with front and rear radars for perceiving objects. Sensors are considered idealistic in the simulations [26], i.e when the vehicles perceives any object in the simulation through its sensors, then it is assumed that the information such as speed, positions, and other related to the perceived vehicle is readily available for the perceiving vehicle. For a vehicle to be perceived, any corner of its dimensions should overlap with the sensor perception range without any obstacles in the sensor line of sight [22], [26]. The sensor configuration for vehicles is inspired by the sensor configuration of Tesla autopilot cars[8]. The front radar is configured with a long range of 160m but with a narrow angle of 35°, whereas the rear radar is considered to have a wide angle of 325° but with a short range of 80m.

The value of the middleware update is considered similar to the value of RRI of 100 ms, since the minimum time interval for the generation of CPM is 100 ms. A lower value of 25 ms was evaluated, but there was no significant difference in the results obtained in this simulation scenario. Simulations were performed with different VPR, to observe the CP service performance; the penetration rates used are 25, 50, 75 and 100.

[7] https://sumo.dlr.de/docs/Tools/Routes.html#cutroutespy
[8] https://www.tesla.com/autopilot

Parameter	Value
Protocol stack	LTE-V2X
Frequency band	5.9 GHz
Frame Structure	FDD
Modulation Scheme	QPSK
Channel model	Winner II C2 variant
RRI	100ms
Allowed subchannel sizes	10, 12, 15, 20, 25, 50, 75, 100
Channel bandwidth	10 MHz
C_{resel}	[5,15]
Number of eNodeBs	11
VPR	0.25,0.5,0.75,0.1
Scenario	InTAS
Time of simulation	06:06 am
Number of vehicles	≈ 1000
Simulation time	8 s (including 4 s of warmup)
Number of repetitions	3
Vehicle sensor equipment	2 radars: (Front - 160m, 35°), (Rear - 80m, 325°)
Area of relevance	500 m
Artery-C middleware update	100 ms

Table 4.1 – Summary of configured simulation parameters

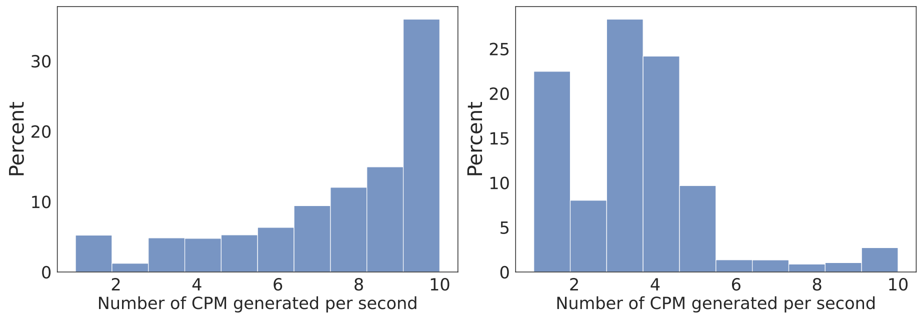
4.2 Analysis of generated CPM

The CPM generated in the simulations are analyzed on the basis of 2 factors, number of CPM generated per second, and message size of the generated messages. The VPR used for this analysis is 100%, that is, all vehicles are capable of generating CPM messages.

4.2.1 Number of CPM generated per second

The frequency of CPM generated depends on the different conditions for ETSI and ETSI-K; therefore, the number of CPM generated varies. But with models considering fixed interval, generates a fixed number of messages per second. Therefore, only the ETSI and ETSI-K models are analyzed. The histogram representation of data is shown in Figure 4.2 for the ETSI and ETSI-K models.

The histogram distribution of the number of CPMs generated per second for ETSI-K shows that more than 85% times the messages are generated with a lower frequency of less than 5 messages per second. But it is also observed that 50% times, the messages are generated in the range of 300 to 500 ms. In case of the model ETSI, the frequency of message generation is very high with 35% of time vehicles



(a) Model ETSI **(b)** Model ETSI-K

Figure 4.2 – Histogram distribution of number of messages generated per second for the ETSI and ETSI-K models

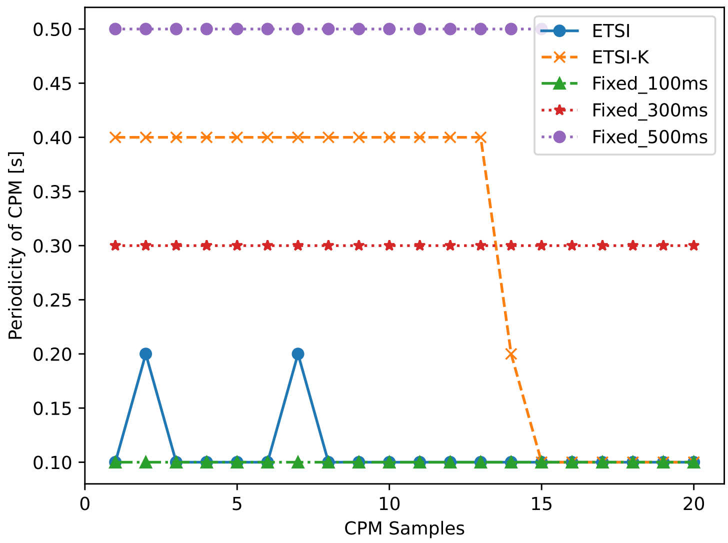


Figure 4.3 – Plot showing the periodicity of the CPM generated with different models

generating 10 messages per second. And the data distribution shows that more vehicles generate more than 5 messages per second.

This variation in periodicity is due to the different traffic densities in different areas of the map used. Vehicles in high-traffic areas such as highways or city-center roads detect a lot of vehicles and hence generate CPMs often for vehicles generating with Model ETSI. For Model ETSI-K, as discussed in 3.2, the generation of CPM depends not only on the objects perceived but also on the dynamics of the ego vehicle. As vehicles reduce the speed to wait for traffic signals, it results in increasing the time interval between two generated CPMs. This behavior is appropriately observed in Figure 4.2b where more than 85% generate less than 5 messages per second. Another reason may be that vehicles in the low-density area view few or no vehicles in their sensor perception range. Therefore, generating messages with lower frequency. In case no vehicles are perceived, the ego vehicle sends only sensor information every second.

The periodicity of 20 CPM messages taken from a random vehicle of the simulation is shown in Figure 4.3. It can be observed that Model ETSI closely follows the generation pattern of Model Fixed 100ms and Model ETSI-K can be compared with Model Fixed 300ms. This observation is true for most of the CPM messages generated, as seen in the histogram representations. To conclude, the behavior observed shows that both the ETSI and ETSI-K models vary the generation of periodicity depending on the traffic scenario the vehicle is in. The observations show that the generated CPM messages can be considered periodic for short intervals of time. However, it should be noted that vehicles can generate aperiodically based on objects detected in the simulations. The variation of periodicity has a major effect on the wastage of resources. As the value of RRI is considered constant in the scope of this thesis. Hence, the resources allocated are wasted when the time interval between messages is greater than 100 ms. This is true for models with fixed interval and can be noted as a drawback observed with the simulations done in this thesis work.

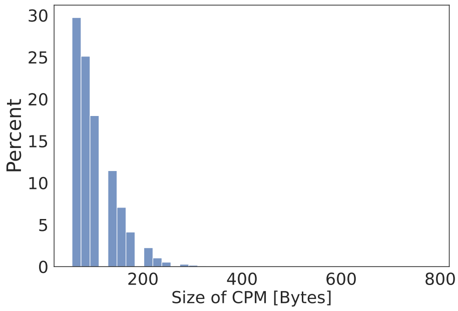
4.2.2 Message size

In this section, we analyze the size of the messages generated in this simulation. As discussed in Section 2.2.2, the size of each CPM is influenced by various factors such as how many objects are perceived by the vehicle or whether sensor information is added to the CPM message. Also, based on the different message-generating models in our simulation work.

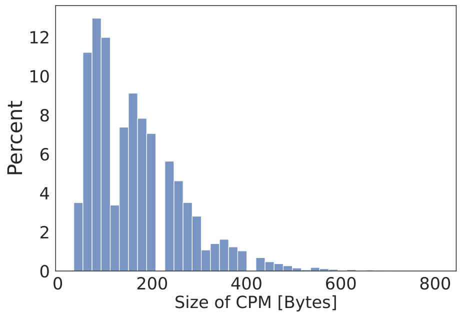
CPM message element	size in bytes
ITS-PDU Header	27
Sensor information container	23
Each object in POC	25
Station and management container	7

Table 4.2 – Individual element size in bytes for generated CPM

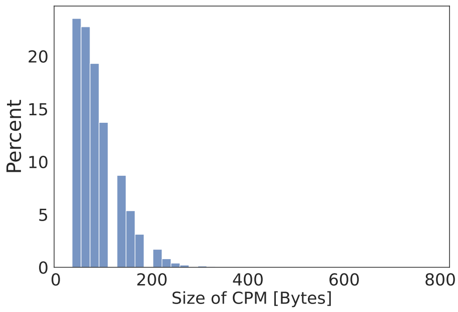
The sizes of the individual elements included in the generated CPM are given in Table 4.2. In the case of fixed periodic interval models, the CPM is generated even if there is no information on the sensor or perceived objects. Hence, the minimum size of the generated CPM is 34 bytes containing 27 bytes of the ITS-PDU header and 7 bytes of SMC. But in the case of the ETSI model, 59 bytes is the minimum, with an



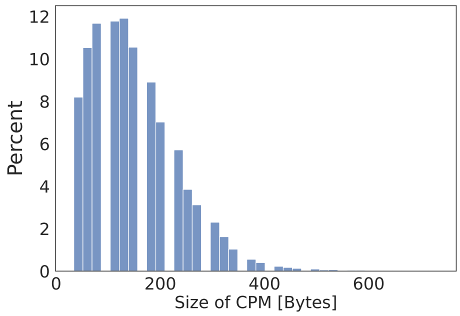
(a) Model ETSI



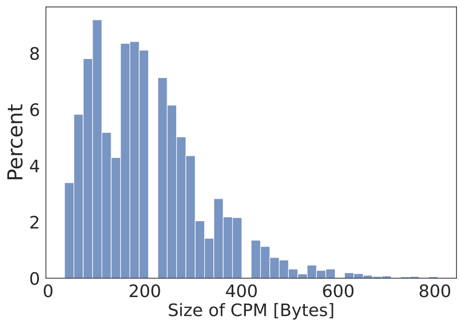
(b) Model ETSI-K



(c) Model Fixed 100ms



(d) Model Fixed 300ms



(e) Model Fixed 500ms

Figure 4.4 – Histogram representation of message size variations for different models used for CPM generation

object of 25 bytes in POC and 7 bytes with SIC. If no objects are detected but only sensor information is passed, then 57 bytes. The increase in the size of the CPM is directly proportional to the number of objects added in POC. In the simulations conducted, CPMs of size up to 800 bytes are observed.

The distribution of the CPM sizes generated for the models used is shown in Figure 4.4. With model Fixed 100ms (Fig. 4.4c) generates more than 50% of its messages with less than 100 bytes, especially around 20% of the values are the minimum, that is, without any object information. The reason is that addition of

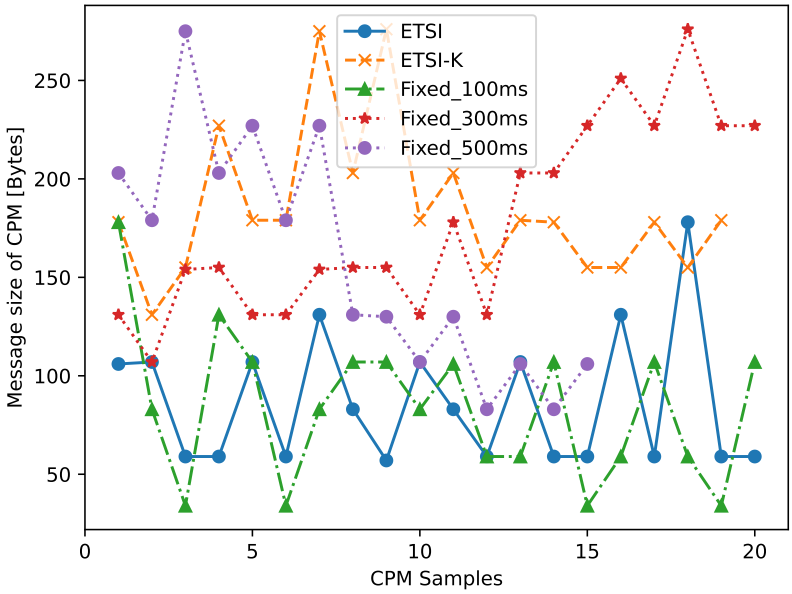


Figure 4.5 – Variations of message size for different models of message generation

objects is dependent on the dynamics of the object; with 100ms there is not much change and the object if it has been included in the previously generated CPM; hence, it is not added in the message. As we observed in Section 4.2.1, the CPM generation behavior of Model ETSI (Fig. 4.4a) is similar to that of the Fixed 100 ms model. Even with the generated size of CPMs, similarities can be observed. More than 70% of the generated CPM are around 100 bytes, specifically 55% are less than 100, indicating that the generated CPM includes information of only one or two objects if sensor information is not included.

For the ETSI-K (Fig. 4.4b) and Fixed 300ms (Fig. 4.4d) model, the distribution is similar, most messages are sent in the range of 50 to 200 bytes including information of objects in the generated messages. The Fixed 500ms model, generates messages with more sizes compared to those of all other models as the time interval between message generation is greater, the dynamics of more objects in the perceived object range would have crossed the threshold, resulting in the inclusion of its information in the generated CPM. As the generation of messages are independent of whether the vehicle is in managed or unmanaged mode, all the histogram plots are done from simulation results of managed mode.

Figure 4.5 shows the variation of the CPM sizes of 20 messages sent by a single vehicle with different models. It can be observed that the sizes of generated messages are not constant and the variation is quite high. Due to these variations, especially the increase in the message size causes issues with unmanaged mode operation of the C-V2X as the resource grant has to be broken to allocate for the newly received message. And as discussed in Section 2.1.2.3, along with breaks in resource grants, the variation also results in waste of resources utilized in the resource pool.

4.3 Evaluation results

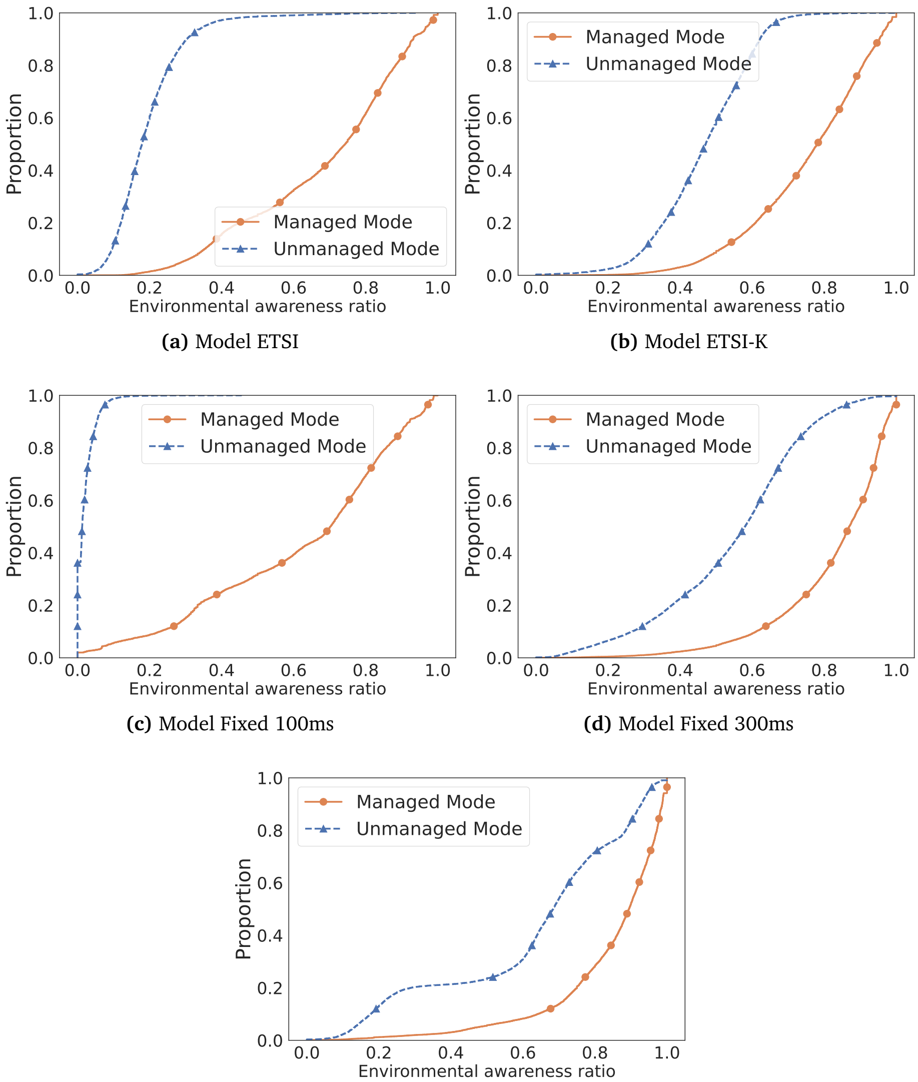
The performance of the collective perception service is measured using three metrics, Environmental Awareness Ratio (EAR), Time Between Updates (TBU), and end-to-end (ETE) delay. With the metric EAR, the measure of the increase in the perception range of the ego vehicle is measured. Whereas TBU, gives information on how frequently the information of tracked objects is updated. ETE-delay, provides estimate of time consumed to pass information from sender to receiver with C-V2X.

4.3.1 Environmental awareness ratio

Environmental Awareness Ratio is defined as the ratio of objects known to the vehicle from CPM messages to the vehicles actually present in Area Of Relevance (AOR). AOR[22] is considered 500 m in this simulation based on C-V2X awareness range[27]. EAR metric gives information on the increased perception range of the vehicle with information on objects received from CPM.

The Empirical Cumulative Distribution Function (eCDF) plots showing the distributions of managed and unmanaged modes for all models are shown with Figure 4.6. The solid line with the circle marker represents managed mode, and the dashed line with the triangle marker represents unmanaged mode. And markers are set for every 10,000 values of the data set. The data used for the graphs are from simulations with VPR set to 100%, that is, all vehicles capable of sending CPM messages. For better performance, the EAR values obtained should be larger; a value close to 1 indicates that all vehicles in AOR are known to the ego vehicle.

Comparing the distributions of managed mode, the Fixed models of 300ms (Fig. 4.6d) and 500ms (Fig. 4.6e) have relatively the same distribution, and perform better than the other 3 models. In both Fixed 300ms and 500ms, 80% of the recorded values are more than 0.8 indicating that most of the vehicles are known to the ego vehicle. But for all models, it can be observed that vehicles operating in managed mode perform better than those operating in unmanaged mode. In managed mode, a dynamic algorithm is used for allocating resources, that is, each vehicle requesting the resources every time it has to transfer the messages. As all vehicles operating in the coverage area will be registered with eNB, whenever there is a request for resource allocation, eNB can handle the request more efficiently. Vehicles operating



(a) Model ETSI

(b) Model ETSI-K

(c) Model Fixed 100ms

(d) Model Fixed 300ms

(e) Model Fixed 500ms

Figure 4.6 – eCDF plots comparing the performance of the managed and unmanaged mode of C-V2X for the metric EAR. Different sub-figures show the plots for different message generation models.

in an unmanaged mode do not have knowledge of other vehicles and resource allocation is based on SB-SPS as discussed in Section 2.1.2.2.

SB-SPS suffers from problems with handling messages of different sizes, as presented in 2.1.2.3. Once a message is received, along with the current transmission, the resources are allocated with the future transmission for a certain number of times defined by cResel, and these can be considered as resource grants. One of the reasons these grants can break is when a message which is supposed to be sent in future allocated resources requires more resources than the allocated one. The broken grant leads to discarding the allocated resources and allocating new resources. It should be noted that the LTE-V2X does not have a mechanism to inform other vehicles about the free available resources due to this reallocation. Therefore, other vehicles continue to consider that resources are occupied and avoid them for selection, resulting in resource wastage. If the grant breaks are quite often and there is continuous request for new resource, then the sensing window will be overloaded. This results in vehicles delaying the packet transmission, which might result in vehicles receiving the CPM after the latency deadline of CPM, that is, one second. As multiple vehicles try to select resources approximately at the same time, there will be overlapping in the selection window timings. The consequence of having multiple vehicles having the same selection window is that, unknowingly, vehicles select the same resource to send messages that result in a packet collision at the receiver [5].

The effects of these grant breaks can be clearly seen with the unmanaged mode of Model Fixed 100ms (Fig. 4.6c), with 90% of the recorded EAR values being less than 0.2. This indicates that most of the CPM messages are not received and the ego vehicle knows only 20% of the vehicles. Due to the shorter periodic interval, there is a continuous request for resource allocation from all the vehicles, and the resource pool is limited. And if there is increase in the size of the messages, then grants are allocated quite frequently, virtually making all the resources in the pool as occupied. This continuous reallocation also leads to an overlap of the selection window for more vehicles. In case of Fixed 300ms and 500ms model, the frequency of request is reduced resulting in more available resource in the pool which can be used for re-selection even though grants are broken due to variation in message sizes. The ETSI model(Fig. 4.6a) shows little better performance than that of Fixed 100ms model, but still worse than other models with more than 80% of its values are less than 0.3. Having considered dynamics of ego vehicle in ETSI-K(Fig. 4.6b) gives more time for resource allocation in high-density traffic signals. The periodicity of generated CPM is less compared to that of ETSI and Fixed 100ms. More than 50% of its values cross 0.6 and its similar to that of Fixed 300ms. This is expected as both periodicity and message sizes are similar. Compared to other models, Fixed 500ms performs better, but still less than that of managed mode.

The analysis of message sizes in Section 4.2.2 shows that the size of CPM messages is small in the case of Fixed 100ms and ETSI models. That is, in more than 50% of the cases, the messages include only one or two objects. As inclusion of an object is dependent on the dynamics of the object, with a shorter periodic interval, there would not be much changes. If the messages with this information are lost, the receiving vehicles will be unaware of the detected objects. In case of Fixed 300ms and 500ms, the CPM includes more number of objects. Hence, even though there are few messages that are lost, receiving one message will inform the receiver with information about the vehicle present. The message received is also affected with hidden terminal problem in case of unmanaged mode, if a vehicle is in awareness range of two other vehicles which are unknown to each other and transfer the V2X message in same resource pool, then the packet is lost at the receiving vehicle. And, both the managed mode and the unmanaged mode are affected by the half duplex property of the sidelink [7], a vehicle cannot send a message in the allocated resource pool if at the same time it has to receive the message.

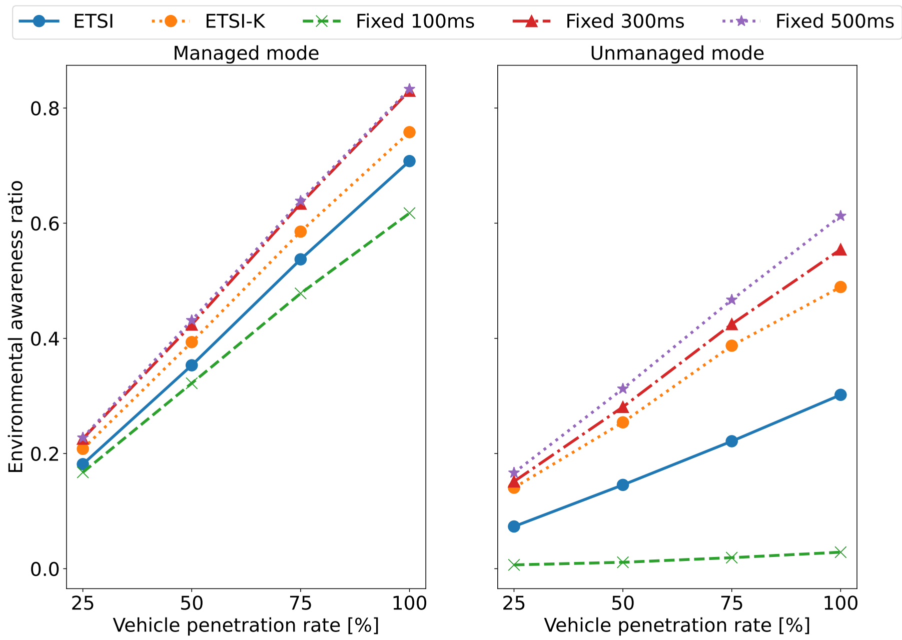


Figure 4.7 – Comparison of the environmental awareness ratio in managed and unmanaged modes with different vehicle penetration rates for different message generation models.

Figure 4.7 shows the different values of EAR for managed and unmanaged modes with different VPR. For lower VPR, vehicle awareness is low, because only a few vehicles are capable of transmitting V2X messages. If we observe the density of vehicles in the simulation scenario used in Figure 4.1b, the region where there is a low density of vehicles will have less information on its surrounding vehicles as there are fewer vehicles sharing information. As VPR increases, more vehicles share information perceived by their sensors. Due to this, the values of EAR increase linearly with increasing VPR.

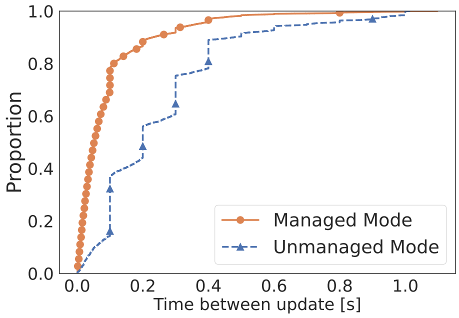
The ETSI and ETSI-K values are close in managed mode, but with unmanaged mode, ETSI-K clearly performs better because more message is transferred with information of more objects. The values of Fixed 300ms and 500ms for unmanaged mode overlap with each other in unmanaged mode, but in managed mode Fixed 500ms performs better compared to 300ms. With both 500ms and 300ms the number of objects added in the generated CPM messages is fairly similar (Figure 4.4d and Figure 4.4e). Hence, the information of the object is frequently received if there is successful transfer of CPM messages, which happens in the case of managed mode. But in the case of an unmanaged mode, the request for allocation of resources is greater and becomes affected by issues of SB-SPS, as previously discussed. It can also be observed that at VPR of 25%, all models have approximately the same EAR value in managed mode, and as the penetration rate increases, the mode that successfully transfers a greater number of CPM messages performs better.

4.3.2 Time between updates

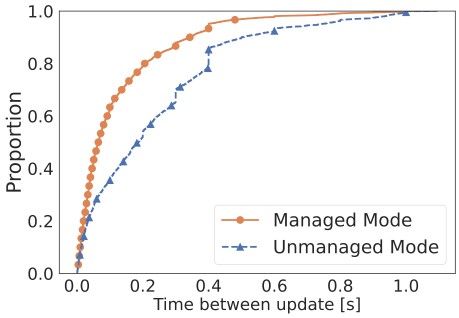
The TBU metric can be defined as the time difference between the updates received for tracked objects in the ego vehicle with subsequent CPM messages. This metric helps us to understand the frequency with which the vehicle receives information about the tracked object. The update messages received are not limited to the vehicle that first sent the information about the object; it can be received from any other neighboring vehicle that perceives the same object. The metric TBU is influenced by different factors, such as how frequently the object information is included in the CPM, how frequently the CPM messages are sent and obviously on how many CPM messages are received successfully.

The eCDF plots of all models are shown in Figure 4.8. The data plotted are for simulations with VPR configured to 100%. The managed mode data is represented with solid lines marked with dots, and unmanaged mode with dashed line and triangles as markers. The marker is set for every 1 million data points. The maximum time object is tracked without the update in vehicle according to standards [12] is 1.1 seconds. The more frequently the update is received, the better the performance. As the CPM received after 1 second is considered stale and not processed, the value of the data ranges from 0 to 1.

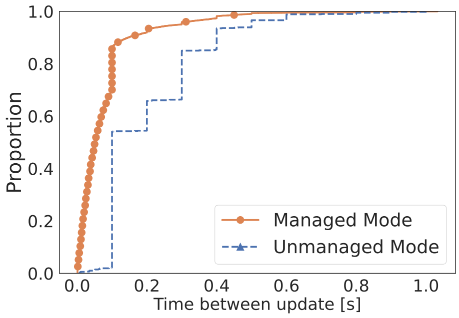
From the data points plotted in the plots, we can clearly observe that in managed mode, vehicle receives updates more frequently compared to that of unmanaged mode. The interesting observation is the update frequency in Fixed 100ms model (Fig. 4.8c), where the unmanaged mode has not even received one million updates, but the managed mode has received more than 40 million updates. This comparison shows how the managed mode successfully handles all requests, while SB-SPS suffers severely when there are more requests. As discussed in the evaluation of EAR (Sect. 4.3.1), the bad performance is due to the frequent message generation, and the generated messages vary in their sizes. Due to this, the resource grants allocated for subsequent transmission are frequently broken, eventually leading to packet



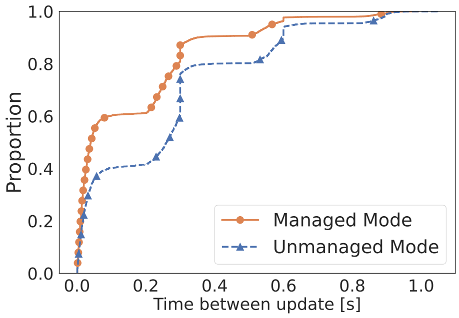
(a) Model ETSI



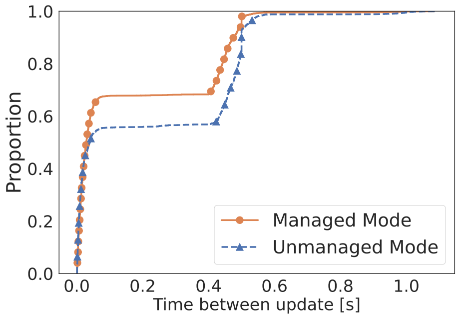
(b) Model ETSI-K



(c) Model Fixed 100ms



(d) Model Fixed 300ms



(e) Model Fixed 500ms

Figure 4.8 – eCDF plots comparing the performance of the managed and unmanaged mode of C-V2X for the metric TBU. Different sub-figures show the plots for different message generation models used.

collisions or delay with transfer of message. Even though the messages are generated every 100ms, only half of the messages are received within 100ms, and the rest are received with a longer delay. The behavior of ETSI model (Fig. 4.8a), is similar to that of Fixed 100ms, but unmanaged mode received more updates as messages are generated at lower frequency. Still, compared to managed mode, the updates received are much lower.

Comparing the plots for ETSI-K (Fig. 4.8b) and Fixed 300ms (Fig. 4.8d), it can be observed that the update pattern for both models is different, even though we can see that the more values are in the same ranges from 0 to 0.6 seconds. As ETSI-K message generation depends on ego vehicle kinematics, the values are spread more evenly but in the case of Fixed 300ms model, the updates are more received around in 3 intervals from 0 to 0.1 second, 0.2 to 0.3 second and near 0.6 second. This is mainly because when the vehicle starts tracking, it receives updates immediately from all its neighbors about the same object. The next message is generated after the interval of 0.3 and 0.6 seconds, explaining more updates near 0.3 and 0.6 seconds. Similar update trends are observed with Fixed 500ms (Fig. 4.8e) for both modes.

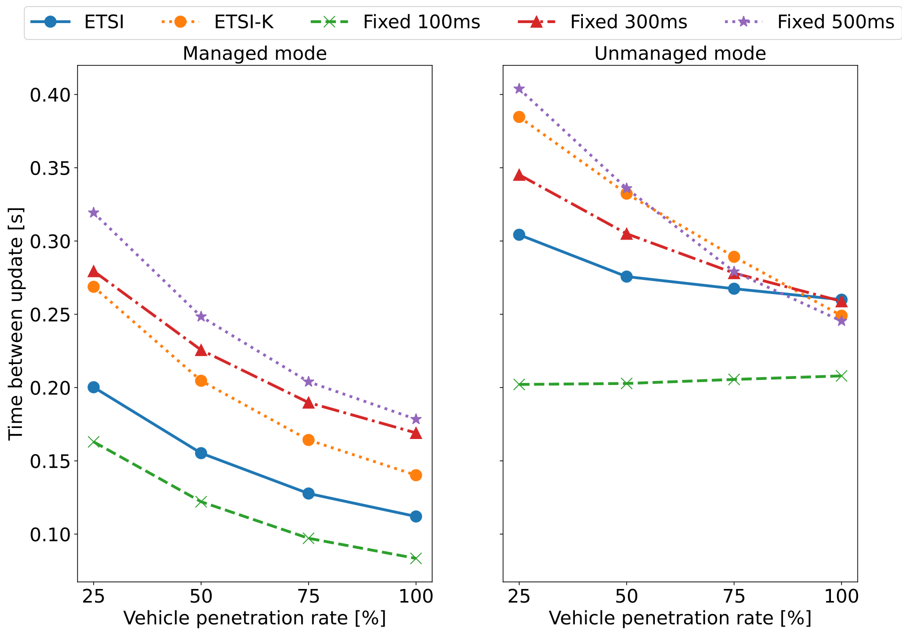


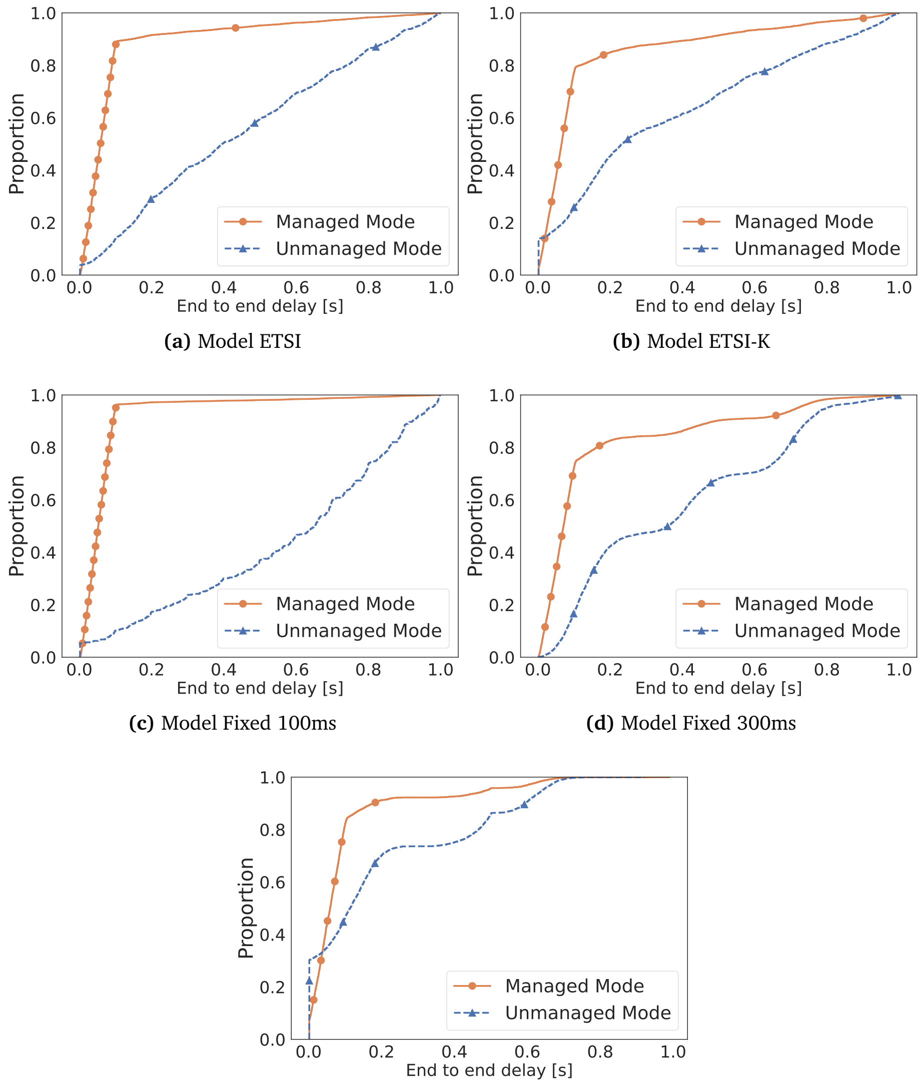
Figure 4.9 – Comparison of the time between update metric in managed and unmanaged modes with different vehicle penetration rates for different message generation models.

The variation in the values of TBU for managed and unmanaged modes with different VPR is shown in Figure 4.9. It can be observed that the values of TBU decrease with increasing VPR as more vehicles send information of the object, and in the receiver vehicle it is refreshed frequently, resulting in lower values. In comparison, for all penetration rates, managed mode performs better than unmanaged mode due to more reliable packet transfer. For Fixed 100ms model, instead of decreasing, there is a slight increase in the values as it faces issues with resource allocation with varying message sizes in high-density traffic scenarios. It should also be noted that, in unmanaged mode as the penetration rate increases, the Fixed 500ms performs better than both the ETSI-K and Fixed 300ms model. The possible reasons could be that more information of objects are included in the CPM from different vehicles and also that more CPM messages are successfully received.

4.3.3 End to end delay

The time taken from the creation of the CPM in the sender's facilities layer to the reception in the receiver's facilities layer is calculated as the ETE delay. This delay includes the time taken in all the layers of C-V2X, including the delay in synchronization and resource allocation of the access layer. It is necessary to have this delay within the limit of 1 second; according to standards, objects with no updates more than 1.1 seconds should be removed from tracking. Therefore, it is necessary for the CPM message to be received under specified latency limit of 1 second to consider it as a valid CPM. The simulation configuration is considered to have good channel quality, and hence it is assumed that there is little propagation delay. The main reason for the delay is the delay in synchronization and resource allocation caused in the MAC layers of C-V2X. In managed mode, dynamic scheduling is used as a resource allocation strategy, which requires requesting eNB for resources every time the message needs to be sent. For the unmanaged mode, the delay is to choose resources autonomously through SB-SPS. In SB-SPS, if there is already a grant allocated and the message received from the facility layer fits the allocated resources, it is sent directly, causing a lesser delay. But in case there is a need to reallocate, then the vehicle needs to sense the channel for the free resource and choose among them while filtering the occupied resources as explained in section 2.1.2.2. This process causes significant delay and if there is a need for continuous reallocation as in case of CPM due to varying message sizes, then the overall average delay increases.

Figure 4.10 shows the comparison of the ETE delay for managed and unmanaged mode for VPR 100% for different models using eCDF plots. For all the message generating models, in managed mode, the frequency of messages received within the required latency limit of 1 second is very high compared to that of the unmanaged mode. Even with the overhead of communicating with eNB, the managed mode latency for all models is lower compared to the respective unmanaged mode, and the delay values of 80% of received messages are within the range of 100 ms. In the case of the unmanaged mode, as we have seen other metrics, the values of Fixed



(a) Model ETSI

(b) Model ETSI-K

(c) Model Fixed 100ms

(d) Model Fixed 300ms

(e) Model Fixed 500ms

Figure 4.10 – eCDF plots comparing the performance of the managed and unmanaged mode of C-V2X for the metric ETE delay. Different subfigures show the plots for different message generation models used.

100ms model (Fig. 4.8c) are worse due to more resource allocation latency. This is due to frequent grant breaks that cause fewer or no available resources in the resource pool. Vehicles have to wait longer than usual to allocate resources to send messages, eventually when that delay crosses more than 1 seconds; then the CPM message will be considered stale even if it gets a resource and is received by its neighboring vehicle. Similarly, for the ETSI, ETSI-K and Fixed 300ms (Fig. 4.10a, 4.10b, and 4.10d, respectively) models, the values of unmanaged are more spread,

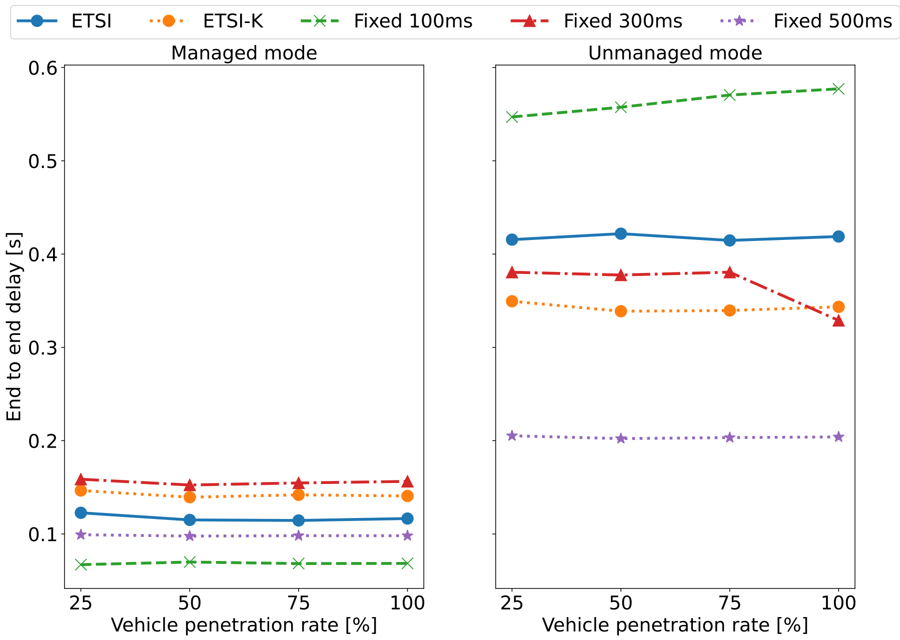


Figure 4.11 – Comparison of the end to end delay metric in managed and unmanaged modes with different vehicle penetration rates for different message generation models.

indicating more delay. But Fixed 300ms have received more messages with a lesser delay compared to that of the ETSI and ETSI-K model, and Fixed 500ms (Fig. 4.10e) are even better than Fixed 300ms. This is seen in previous metrics that the SB-SPS algorithm performs better with messages generated with periodic intervals. And a larger periodic interval gives more time for SB-SPS to deal with the adversity caused by variation in the message sizes. Figure 4.11 shows the comparison between different penetration rates of vehicles. For both the unmanaged and managed modes, the values remain fairly equal for all penetration rates.

Chapter 5

Conclusion

In this thesis work, the CP service was evaluated with the stack of LTE -V2X, through simulations performed with the traffic model that closely matches the real-world traffic of the Ingolstadt city. Different models were used to vary the periodicity of CPM generation, and the results of these models were compared with the baseline model following the CPM generation rules of the ETSI model. The simulation results show that for all the metrics and all the message generating models; managed mode has better performance compared to that of unmanaged mode. With the simulation results, it can be concluded that the SB-SPS resource allocation strategy is severely affected by the high variation of generated message sizes, especially when messages are generated with a higher frequency. With the ETSI-K model, the ego vehicle dynamics was used to reduce the frequency of message generation, specifically for areas with high density. And a slight improvement in the performance was observed compared to the ETSI model. The reduced frequency of message generation helped SB-SPS better cope with the adversities of the change in the size of the messages generated. The Fixed 300ms and 500ms results indicate that a fixed and larger interval between the messages improves performance. With the results of the EAR metric evaluation, it was observed that even though the periodicity of the messages was reduced, the benefit of improved environmental perception was not affected. In future research work, it is necessary to analyze the benefits in terms of resource utilization in the C-V2X access layer with different RRI values. And, to reduce the number of grant breaks due to variation of message sizes, the information of allocated size can be informed to facilities layer. Using this information, the size of CPM messages can be reduced to remove objects by incorporating different object redundancy mitigation techniques. Furthermore, the 5G-NR stack can be used and the results can be compared to understand the benefits of the proposed techniques, such as passing the cResel values with SCI.

Future vehicles operating in the age of automated driving require information beyond the perception range of mounted sensors, and this information must be as accurate as possible. This precision is necessary to use shared data for critical safety applications, and reliable communication channels are required to make this a reality. Current standards of C-V2X lack the ability to handle this kind of communication without the help of eNBs. As seen from the simulation results of this thesis work, vehicles in the coverage area can benefit more choosing to operate in managed mode instead of unmanaged mode. Although communication is more reliable with eNBs, it is impractical to assume that cellular infrastructure will be available in all parts of the world. Therefore, it is necessary to bring improvements for resource allocation algorithms of unmanaged mode; the simulation results show that reducing the frequency of message generated improves the performance. However, more research is needed to verify whether this reduction is feasible for all V2X application scenarios.

List of Abbreviations

3GPP	Third Generation Partnership Project
ADAS	Advanced Driver Assistance Systems
AOR	Area Of Relevance
ASN.1	Abstract Syntax Notation.1
BSM	Basic Safety Message
C-V2X	Cellular-V2X
CAM	Cooperative Awareness Message
CP	Collective Perception
CPM	Collective Perception Message
DENM	Decentralized Environmental Notification Message
DSRC	Dedicated Short Range Communications
EAR	Environmental Awareness Ratio
eCDF	Empirical Cumulative Distribution Function
eNB	eNodeB
ETE	end-to-end
ETSI	European Telecommunications Standards Institute
GEM	Global Environmental Model
ITS	Intelligent Transport System
LEM	Local Environmental Model
LTE	Long Term Evolution
POC	Perceived Object Container
RB	Resource Block
RRI	Resource Reservation Interval
RSRP	Reference Signal Received Power
RSU	Road Side Unit
SB-SPS	Sensing Based Semi-Persistent Scheduling
SCI	Sidelink Control Information
SIC	Sensor Information Container
SMC	Station and Management Container
SPS	Semi-Persistent Scheduling

TB	Transport Block
TBU	Time Between Updates
UE	User Equipment
V2I	Vehicle-to-Infrastructure
V2N	Vehicle-to-Network
V2P	Vehicle-to-Pedestrian
V2V	Vehicle-to-Vehicle
V2X	Vehicle-to-Everything
VPR	Vehicle Penetration Rate

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