POLITECNICO DI TORINO

Master degree course in Communications and Computer Networks Engineering

Master Degree Thesis

Cellular communications between vehicles and everything(C-V2X): integration and first prototype

Supervisors:
prof. Carla Fabiana Chiasserini
prof. Claudio Ettore Casetti

Candidate
Kalkidan T. Gebru

ACADEMIC YEAR 2017-2018

‘Trust in the Lord with all thine heart; and lean not unto thine own understanding. In all thy ways acknowledge him, and he shall direct thy paths.’

Acknowledgements

I would first like to thank my thesis advisers prof. Carla Fabiana Chiasserini and prof. Claudio Ettore Casetti who have accepted me to join this project. Prof. Chiasserini has been the main guide, and she with prof. Casetti have been supporting me through discussions and suggestions. I then would like to thank Giuseppe Avino and Marco Malinverno who are the main developers of collision detection prototype, for all their technical and idea support. I would also like to acknowledge my whole family whose support is with out condition.

My highest acknowledgement and praise is for the one who watches over me day and night providing all my needs, God.

Abstract

C-V2X is a technology introduced by 3GPP 4G standards and designed to allow vehicles to communicate with everything, i.e., other vehicles (V2V), pedestrians (V2P), infrastructure (V2I), and the cloud network (V2N). The technology uses cellular network infrastructure that is already providing service to UEs, with architectural enhancement. C-V2X defines two complementary transmission modes: Direct communication and Network-based communication. Direct communication, necessary for V2V and V2P, is based on the LTE device-to-device communication over the so-called PC5 interface and it can operate both under and out of the coverage of base stations. All other communication modes, instead, leverage the cellular network infrastructure (i.e., the LTE-Uu interface), and require a base station (i.e., an eNB) as intermediator to communicate with an application server in the mobile operator network or in the cloud network.

V2X communication is intended to improve road and passenger safety, traffic efficiency and infotainment services. C-V2X technology enhances safety providing information even beyond the driver's line of sight to notify and warn drivers of possible hazards and of oncoming vehicles. Ultimately, this feature will play a vital role in supporting fully autonomous vehicle deployment. Road safety is one of the use cases in Intelligent Transport System (ITS) among warning applications (i.e, collision risk and others).

In my thesis, I collaborated to develop a working first prototype of a collision avoidance application implementing intersection warning. The prototype is designed to operate considering vehicles and pedestrians (UEs), whose mobility is simulated using SUMO, a well-established mobility simulator. The system relies on Cooperative Awareness Messages(CAMs), which are beacons sent by UEs and Decentralized Environment Notification Messages (DENMs), which are alerts sent by the application server. According to ETSI standards, CAMs are transmitted with a minimum frequency of 1Hz and maximum of 10Hz. In order to detect a potential crash accident, the prototype uses state-of-the-art algorithms based on the trajectory of UEs. The collision avoidance algorithm resides on an application server

and it is run when, after receiving a CAM, it is determined that the sender of the message is on a collision course with another node. The collision detection algorithm requires as input the position and speed (including heading) of the current vehicle, as well as the latest CAM sent by each vehicle in the scenario. The collision avoidance algorithm can distinguish between CAMs sent by pedestrians and CAMs sent by vehicles. This gives us a double advantage. First, when the server receives a CAM from a vehicle, it looks for possible collisions with both cars and pedestrians, while on the contrary, with a message sent from a pedestrian, the algorithm skips the analysis for pedestrian-with-pedestrian collisions. The second advantage involves the possibility to set different parameters for the collision detection algorithm, according to the type of entity which sent the CAM. This allows a better performance of the algorithm, in terms of false positives and false negatives. The experimental study features a realistic scenario including both human driver and autonomous vehicles in an urban environment and it tries to establish the effectiveness of the whole system in preventing collisions between vehicles and between vehicles and pedestrians. It also aims at quantifying the rate of false positives and false negatives and at suggesting possible ways to reduce them.

Contents

List of Tables

List of Figures

Chapter 1

Introduction

Traffic accident studies predicted that accidents would be the seventh major cause of death by 2030 if left unchecked. According to the WHO, risk factors include speeding, driving among alcohol and other psychoactive substances, distracted driving and dangerous road infrastructure. It was recommended to implement government policies and provide technical assistance to prevent injuries. Interventions also include the development of safer infrastructure and the integration of vehicle safety features. Countries and organizations have taken up the subject first by promoting research.

The V2X communication, which relates between vehicles, pedestrians and infrastructure for the exchange of information, has become very popular and has been the subject of numerous studies recently due to its significant potential for intelligent transportation and various security applications. Through V2X communication, manual driving of vehicles and autonomous vehicles can provide useful information to improve traffic safety and support the infotainment service.

Many transportation problems arise from the lack of accurate and timely information and lack of proper human coordination in the system. The positive contribution of information technology to better inform people involved in the system to make synergy decisions.

The V2X safety applications help the driver to have a conscience to 360 degrees of dangers and situations they can not even see. With warnings, drivers and pedestrians will suddenly be alerted to impending collision situations, such as the fusion of trucks, cars in the blind side of the driver or when a vehicle in front brakes. By communicating with the road infrastructure, the driver can be alerted when a school zone enters, when the workers on the edge of the road, and when a traffic light will change.

This work is structured in chapters as follows: Chapter 2 is a background on LTE and its improvement over releases. In this chapter ITS is also included to provide a general information. Chapter 3 is about cellular V2X based on LTE release 14, and it describes the two communication modes, architecture and enhancements. Chapter 4 is about saftey service application, a collision detection application, based on CAM and DENM information exchange. Chapter 5, the final chapter before the conclusion, shows and describes the simulation environment for experiments and the main results of the simulations.

Chapter 2

Background

2.1 LTE

LTE standard has been introduced by 3GPP release 8 as an extension of UMTS. LTE is mainly designed for high speed data applications both in the uplink and downlink offering data rate about 75Mbps and 300Mbps, respectively. Its basic architecture, besides UE, includes two main network components: E-UTRAN and EPC. EUTRAN (Evolved Universal Terrestrial Radio) consists of eNB (Base station) which is responsible for complete radio management, such as allocation of uplink and downlink to UE, radio bearer control and radio admission control. When packet arrives from UE to eNb over the air interface (uplink uses SC-FDMA and downlink uses OFDMA), it is tunneled using the GPRS Tunneling Protocol user Plane (GTP-u) protocol, and sent to Serving Gateway (SGW) which is part of EPC. EPC contains additional entities such as MME, PGW, PCRF and HSS. Mobility Management Entity (MME) is a control entity which is responsible for all control plane operations and it handles the signaling related to mobility and security for E-UTRAN access. It is also responsible for the tracking and the paging of UE in idle-mode. SGW deals with user plane transporting the IP data traffic between the User Equipment (UE) and the external networks. It is responsible for packet routing and forwarding, and acts as local mobility anchor point for inter-eNb handover. PDN Gateway (PGW) is the point of interconnect between the EPC and the external IP networks. It deals with all the IP packet based operations such as deep packet inspection and UE IP address allocation. Policy Control and Charging Rules Functions(PCRF) is responsible for policy control decision making and provides the QoS authorization to decide how data will be treated with respect to user's subscription. Home Subscriber Server (HSS) is a central database that contains user-related and subscription-related information. It also provides support functions in mobility management, call and session setup, user authentication and access authorization.

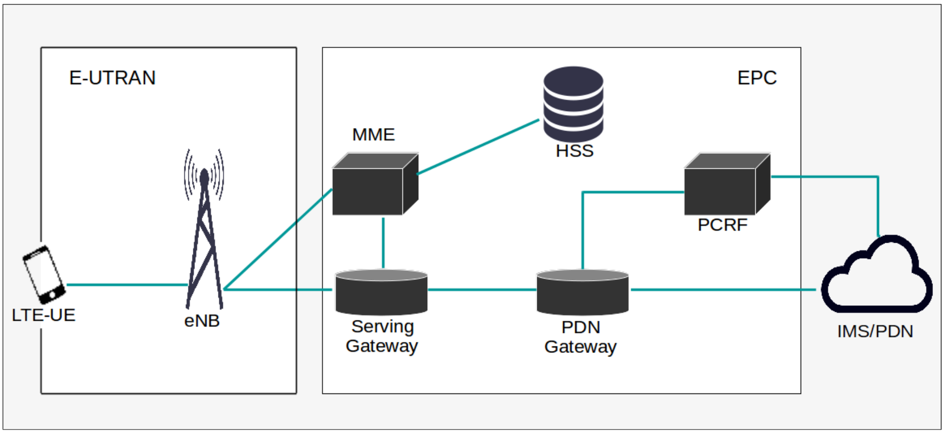


Figure 2.1. LTE architecture

3GPP release 10 is considered as LTE Advanced (LTE-A) after changes in release 9, and it aims higher capacity, i.e., increased peak rate, higher spectral efficiency, increased number of simultaneous active subscribers and improved performance at cell edges. In order to achieve this goal, new functionalities are introduced. One of these is Carrier Aggregation (CA): aims to increase the capacity by aggregating carriers for more bandwidth. The maximum number of carrier components that can be aggregated is 5 forming a maximum bandwidth of 100MHz (a single carrier has maximum 20MHz). The number of aggregated component in DL and UL as well as the bandwidths of individual carriers can be different. The second enhancement is Multiple Input Multiple Output (MIMO) â or spatial multiplexing. This approach aims increasing the bitrate by increasing number of antennas for different data streams. Major change in LTE-A is using 8x8 MIMO for downlink and 4x4 in uplink. In release 9 it was 4x4 for DL and Single Input Single Output (SISO) for UL. Another introduced solution is Relay Nodes (RNs) which enables signals to be forwarded by remote stations from a main base station to improve coverage. These low power base stations, RNs, will enhance capacity at cell edges.

In release 11, the LTE-Acontinued to evolve introducing Coordinated Multi Point operation (CoMP). The main reason behind is to improve network performance at cell edge. The solution provides technique that enable the dynamic coordination of transmission and reception over a variety of different base stations.

Release 12 came with the concept of Device to Device (D2D) communications. LTE D2D communications is a peer to peer link which does not use the cellular network infrastructure, but enables LTE based devices to communicate directly with one another when they are in close proximity.

2.2 ITS

Intelligent Transport Systems (ITS) provide transport solutions to make transport safer, more efficient and more sustainable by applying various information and communication technologies to all modes of passenger and freight transport. Moreover, the integration of existing technologies can create new services. The main concept of ITS is co-operative awareness - the ability of transport entities (vehicles, roadside infrastructure, pedestrians, etc.) to collect knowledge of their local environment, from a range of sensor equipment, and to share that knowledge in order to make more intelligent use of the transport infrastructure. ETSI has defined ITS environment comprising four kinds of ITS stations (ITS-S): Central, road side, vehicle and personal ITS-Ss. Central ITS-S can play a role of traffic operator, road operator, and service or network operator. All ITS stations will communicate each other through a local wireless access point (e.g. ITS G5 based) or a wireless wide area network (e.g. a cellular network) providing ITS application to each other. The standard also defines a common reference communication architecture for all ITS stations.

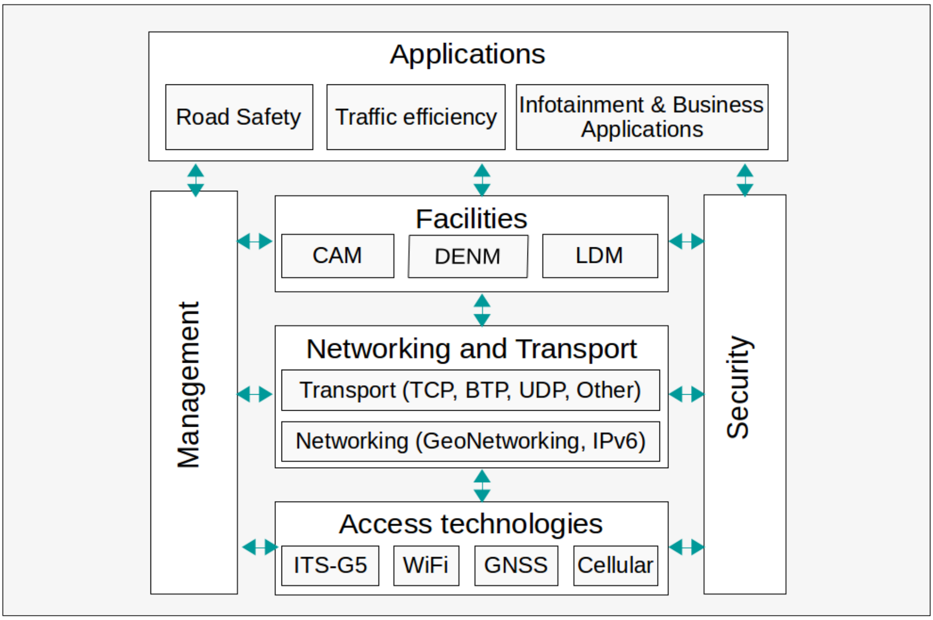


Figure 2.2. ITS architecture

Application layer: Defines three classes (road safety, traffic efficiency and other applications) that provide ITS services, and any ITS application will be defined in on of the classes.

Facility layer: provides generic support facilities to applications. The layer is composed of 3 main components. The first one is application support which is the kernel of common functions supporting applications and defines important messaging through CAM and DENM. The second is information support that covers the role of data management and it collects information from different sources, combines them for use. The last one is communication support and it cooperates with transport and network layer to achieve the various communication modes required by the application.

Network and transport layer: provides services for the layers above it and utilizes the capabilities of the underlying access technologies. The objective is the transport of data between source and destination ITS stations; either directly or multi-hop through intermediate ITS stations.

Access technologies layer: supports different access technologies including ITS-G5, 802.11, cellular and so on. Distinct access technologies should support at least PHY and MAC layers.

Management layer: responsible to ally applications, networks, and interfaces in a specific implementation. This implementation can range from a simple standalone unit in a vehicle (vehicle station) to a complex router/host interaction in a large roadside network.

Security layer: handles firewall and intrusion management, authentication and authorization management, and security information base.

Chapter 3

Cellular-V2X

Cellular-V2X (C-V2X) was initially defined as LTE V2X in 3GPP Release 14. It is designed to provide real-time, highly reliable, and actionable information flows to enable safety, mobility and environmental applications. Even though V2X communication was possible and available in 802.11p technology, cellular-V2X is necessary due to its unique futures such as coverage and line of sight. The LTE based V2X uses the existing LTE infrastructure that already provides wider coverage, better Quality of Service(QoS) for congested scenario, and other various services. Moreover, the rich and fast evolution path towards 5G also makes it preferable for service roll-out.

V2X technology provides best supporting futures with different application types for intelligent service based on LTE system. It includes four kinds of applications: V2V, V2I, V2N and V2P. These applications individually or together can improve services such as road safety, traffic management, infotainment and autonomous driving which are defined in ITS basic set of services. V2V application allows vehicles to communicate with each other using predominantly PC5 interface (direct mode) for information exchange such as dynamics of traffic, location of vehicle and other attributes. If the direct communication range of V2V is limited, the transported information can be forwarded by infrastructure-based V2V communications, such as roadside units (RSU) and application servers. Similar to this one is V2P application where information exchange is between vehicle and pedestrian. Due to battery capacity, the radio capacity of pedestrian is lower than vehicular UEs. Hence, V2P messages are less frequent for pedestrians than vehicular UEs. V2I application is from UE to an application server or rsu and viseversa. The application server is available for a specific geographical area. V2N application is the communication between application server and UEs over the network using Evolved packet switching (EPS). Cellular V2X defines two complementary communication modes over these applications: direct mode (necessarily for V2V and V2P) and network-based (necessarily for V2I and V2N).

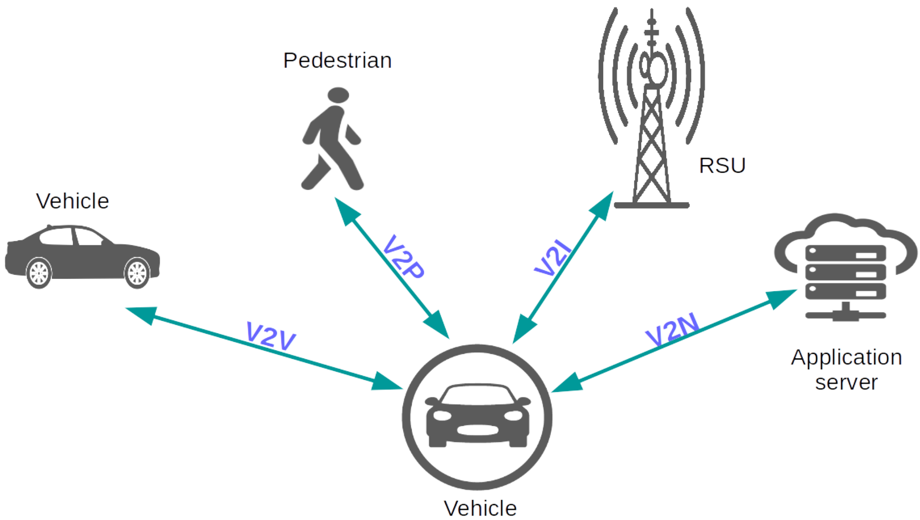


Figure 3.1. V2X application types

3.1 Direct mode

The PC5 interface, originally designed for sideband proximity services, operates at the 5.9 GHz ITS dedicated frequency. A moving vehicle can communicate with other vehicles, pedestrians or UE-type RSUs directly over the PC5 interface without the participation of eNB-type RSUs. Direct communication, referred as sidelink communication, is based on the LTE device to device (D2D) communication proximity based service (ProSe). It is mainly used for V2V and V2P public safety applications that require low latency. This mode can work both in and out of network coverage. We can have both UEs under coverage, both outside of E-UTRAN coverage and one of the two is in coverage. Based on coverage and resource allocation method connection can be established for transmission of V2X messages. Resources can be allocated in two ways; it can be allocated directly by eNB if under coverage or autonomously selected by UEs from pool of resources made available by the network. Resource pool can be subframe pool in time domain or RBs pool in frequency domain with in the subframe pool. All parameters for resource pool allocation are broadcasted periodically by eNB. Regarding coverage, when both UEs are inside E-UTRAN, the network is in control over the radio resources by assigning specific resource to UEs based on the cell scheduling algorithm. UEs looking for transmission grant will request for a resource and the network will allocate and notify them. The process will require extra signaling for every transmission and this with increase the transmission latency. When there is partial or no coverage of UEs the antenna (base station) is unable to manage the multiple transmissions. This situation will lead in to providing pool of resources which in this case the UE will choose from. Even though control is not up to the network, UEs will use pre-configured radio resource which can be set in the UE itself hard coded or in USIM of the UICC card. Here out-of-coverage does not necessarily imply no coverage at all. However, it means there is no coverage on the frequency used for the direct communication while UE might be using cellular traffic coverage.

3.2 Network based

Network-based leverages cellular network infrastructure over Uu interface which serves as an air interface between UEs and eNB, and can operate on frequencies shown in table 3.1 (V2X operating bands). From the V2X applications, V2I and V2N will use the infrastructure. V2V application can also be used but in this case instead of direct communication between UEs the infrastructure(i.e., eNB) is involved forming V2I2V transmission. Unlike direct V2V communication, resource will be divided in to two parts for downlink and uplink transmission. On uplink UEs will send message to eNB and up on successful reception eNB will broadcast using downlink to UEs under its coverage. Additionally, simultaneous LTE-Uu based and PC5 based V2X communications are possible over the infrastructure. For instance, using PC5, V2X messages can be received by a stationary infrastructure entity serving as a UE, such as an RSU. Then, the entity can forward the application layer processed V2X messages to a V2X Application Server using the mobile network. As an alternative to V2X application server processed messages being distributed to UEs through MBMS, the server can send the message to UE-type RSUs over the Uu interface and the RSUs can broadcast the received V2X messages over PC5. UEs within the region will receive the RSU broadcasted V2X messages over PC5. The network-based communication involving eNBs has larger latency than direct communication using sidelink, and a transmission from initial UE to final destination may add more latency even more if it involves more than one base station in between. Therefore, this type of communications are suited for latency tolerant use cases.

Interface	Operating band	Sidelink transmit (MHz) Uplink	Sidelink receive (MHz) Downlink	Duplex mode
PC5	47	5855 - 5925	5855 - 5925	-
Uu	3	1710 - 1785	1805 - 1880	FDD
	7	2500 - 2570	2620 - 2690	FDD
	8	880 - 915	925 - 960	FDD
	39	1880 - 1920	1880 - 1920	TDD
	41	2496 - 2690	2496 - 2690	TDD

Table 3.1. V2X operating bands

3.3 Requirement

V2X service mandates the cellular technology to prioritize and address message exchange requirements based on application aspect(i.e., safety and non-safety). 3GPP has defined basic service requirements such as latency and message size. The latency - maximum tolerable elapsed time from the instant a data packet is generated at the source application to the instant it is received by the destination application - should be low. If message transmission is between two UEs over infrastructure, the maximum latency must not exceed 100ms. Other transmission should be lower than 100ms and direct communication, specially for road safety applications, maximum required latency is 20ms. For non-safety applications, however, the end-to-end delay between UE and application server can be up to 1000ms. Another important requirement is size of the message, i.e., when multicast or broadcast messages are being sent to vehicles within range to either warn them for collision prevention or when an event occurs to inform other vehicle about an accident. For all the use cases, the network should be capable of transferring periodic broadcast messages between two UEs supporting V2X application with variable message payloads of 50-300 bytes, without including security-related message component. For road safety applications the payload can be up to 1200 bytes. Remaining requirements are message frequency which is a maximum of 10Hz per transmitting UE, a communication range that is sufficient enough to give drivers ample response time, and speed requirement supporting a relative velocity up to 500Kmph.

3.4 Enhancement

3.4.1 Physical layer

Sidelink is transmitted by a UE, and is therefore closely related to the uplink, but it also incorporates some aspects of downlink synchronization and control signaling since another UE will be the receiver. During transmission, receiver will have to be synchronized to the sender in order to demodulate the transfered message. When UEs are synchronized in a same cell, moving in a smaller pace, and are under coverage, receiver can demodulate data by balancing the propagation delay. However, when UEs are not synchronized, or one of them is out of E-UTRAN coverage, additional information is needed for synchronization. Moreover, the behavior vehicular communication, that is as the vehicle travels from one edge of a cell to another edge at a speed, a receiver carrier frequency shift called doppler effect will occur. In order to handle synchronization with doppler effect on sidelink, increasing the number of DeModulation Reference Symbols (DMRS) is an available solution. DMRS are reference signals which are used to enable coherent signal modulation between UEs. These signals are time multiplexed with uplink data(sidelink transmitter). To cope up with the high mobility issue, more DMRS symbols are added. The approach considers both high speed of UE up to 250 km/h(and relative speeds of up to 500 km/h), and high frequency (5.9GHz) since the higher the frequency the higher dopper effect too. Unlike LTE D2D, the improvement for frequency alignment and channel estimation uses four DMRS symbols instead of two symbols per resource block (RB) for the PSCCH and PSSCH. Similarly for PSBCH three reference symbols instead of two DMRS symbols per subframe are used.

3.4.2 Scheduling Assignement

SA arrangement

Cellular-v2x uses LTE subchannels to transmit data and control information. The subchannels are group of resouce blocks(RBs) in the same subframe. The number of these RBs assigned to subchannels can be different between the subchannels. Over the subchannels while data is tranmitted over physical sidelink shared channels (PSSCH) in transport blocks (TBs), control information messages are transmitted over physical sidelink control channels (PSCCH).

Previous release (D2Drelease 12) has resource pool structure over the time time domain for PSCCH and PSSCH as shown in the figure 3.4 (resource pool structure). The minimum time duration between two consecutive PSCCH is 40ms which is in contrast to the latency requirement of safety services. According to the standard safety service message transmission over sidelink requires a maximum latency of

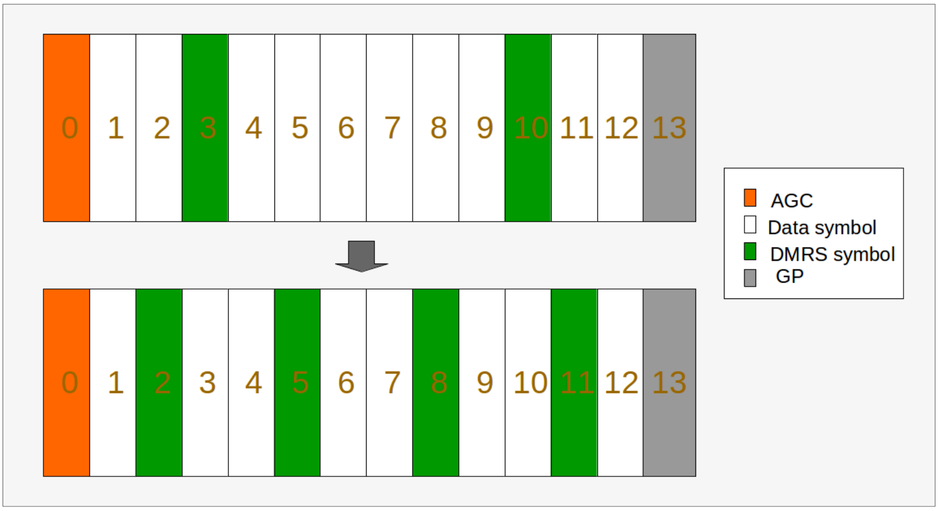


Figure 3.2. DMRS enhancement for PSCCH/PSSCH

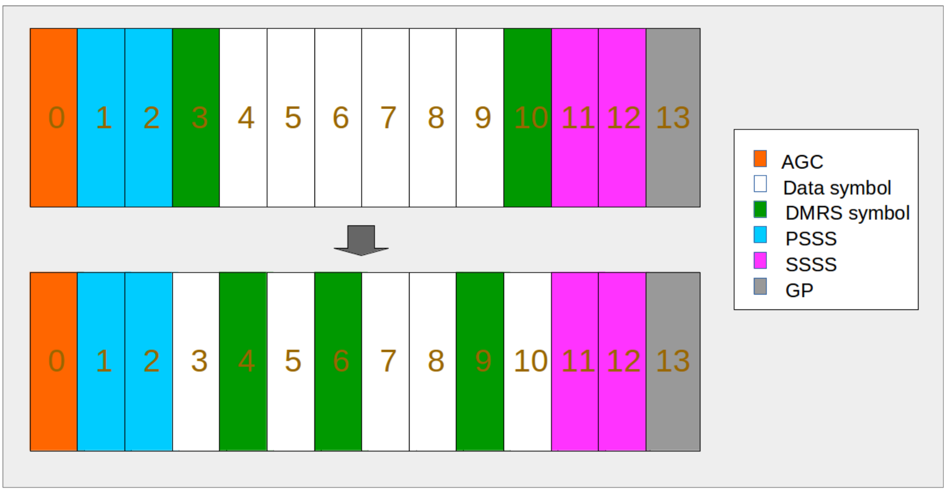


Figure 3.3. DMRS enhancement for PSBCH

20ms. To address latency issue, in release 14 (V2V), SA(PSCCH) pool and it associated data (PSSCH) pool can be over the frequency domain. The control information inside sidelink control information (SCI) includes modulation and coding schemes used for TB, RB it is going to use, and resource reservation interval. A TB which contains a full packet to be transmitted and the associated SCI are transmitted in the same subframe. Transmission of SCI and TB can be adjacent or non-adjacent. If for each SCI and TB transmission, the SCI occupies the first two RBs of the first subchannel then utilization is adjacent. TB can occupy several subchanneles depending on the its size. In this case TB will also occupy following subchannels including the first two RBs used for SCI. In non-adjacent mode, RB are divided in to two pools. While the first pool is used only for transmitting SCI, the other is for TB transmission only.

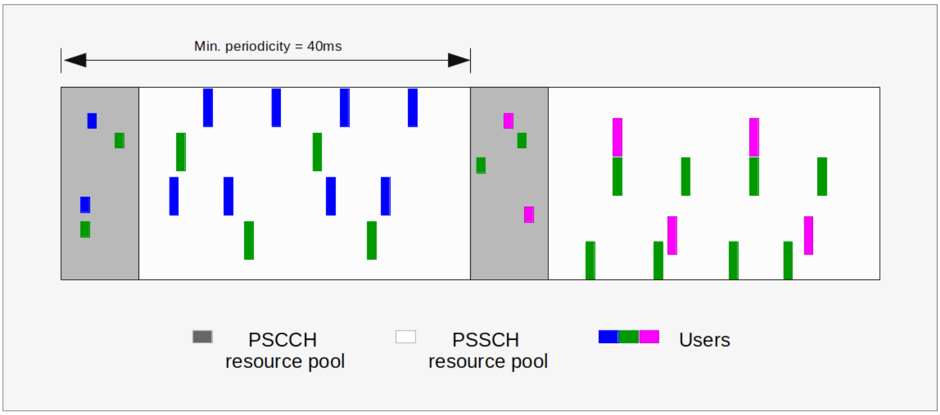


Figure 3.4. Release 12 resource pool structure

SPS

D2D communication in release 12, resource allocation for public safety had 2 modes of operations: mode 1 where communications are assisted by the eNB, i.e., resource scheduling is performed dynamically by the eNB, and mode 2 where UEs manage resource scheduling autonomously relying on pre-configured settings. However, these were not suitable for V2X communication since their design was aimed at prolonging the battery life of UEs, not latency. Additional 2 modes, Mode 3 and Mode 4 were introduced in release 14 for V2X communication. Mode 1 requires extra signaling for every transmission and this will increase transmission latency.

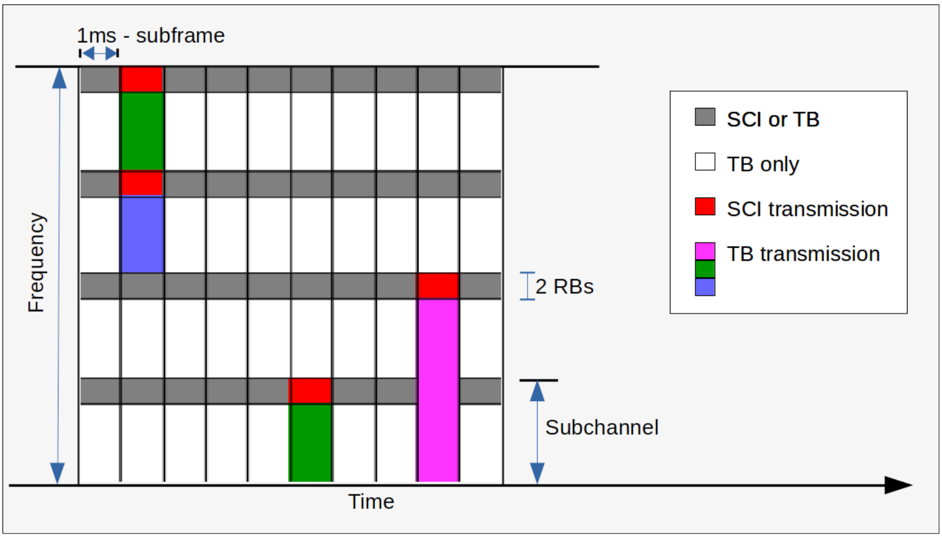


Figure 3.5. Release 14 resource pool structure: adjacent

On the hand mode 2 was able to solve latency issue. However, during the autonomous selection collision and interference may occur as number of UEs grow. In mode 3 the network selects and manage radio resources by assigning to UEs and both communicating UEs must be under coverage. In mode 4, however, UEs will autonomously select radio resources for direct communication and in contrast to mode 3, it works also when UEs are out of coverage.

In mode 4, vehicles select their subchannels using semipersitant scheduling (SPS). These subchannel are reserved for number of consecutive re-selections (counter) which is between 5 and 15. Before making the reservation UE will consider previous 1000 subframes to check if a candidate resource is not in use by another UE in the same time from correctly received SCIs. The candidate time period (selection window) is between T, when UE needs to reserve new subchannels and the allowed maximum latency which is 100ms. After each transmission the counter will decreases until it reaches 0. When the counter reaches 0 or when packet to be transmitted does not fit previously selected subchannels new resource reservation is initiated. Mode 3 can also be merged with SPS. However, it is up to eNB to decide how long the reservation should be maintained, i.e., there is no re-selection counter.

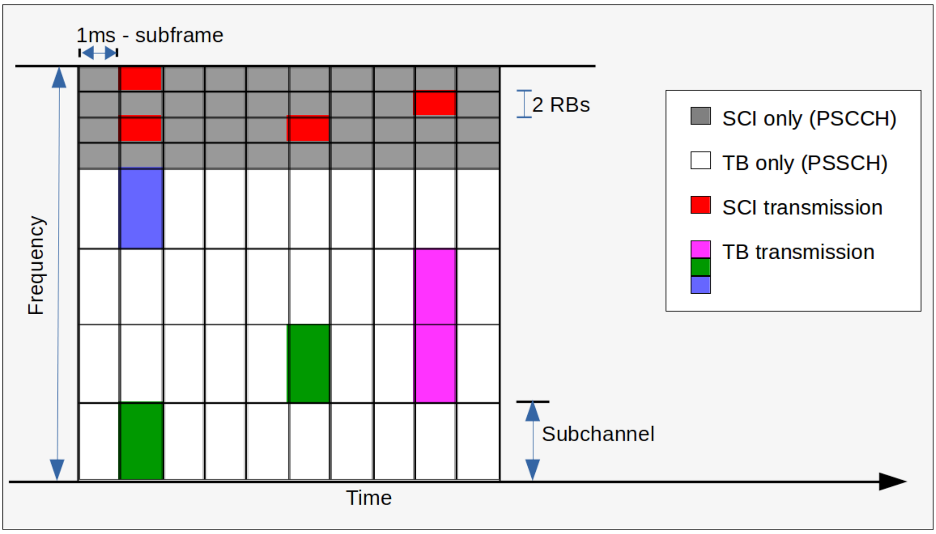


Figure 3.6. Release 14 resource pool structure: non-adjacent

3.4.3 eMBMS

eMBMS was designed for efficient transmission of multicast or broadcast contents to users using LTE infrastructure. Before considering services, such as vehicular communication that require high latency, Multimedia Broadcast Multicast Service over Single Frequency Network (MBSFN) was used to deliver the message. In MBSFN radio channel resources over different cells are timely synchronized in MBSFN area. The MBSFN approach, a one-to-many communication, routes uplink received packets through the network to the relevant BSs before the downlink transmission and eNBs are synchronized before multicasting or broadcasting message. In order to best guarantee latency another point-to-multipoint (P2MP) service, called Single-Cell Point-To-Multipoint (SC-PTM), will use the architecture with more efficient way in the core network of an operator. The late solution will no longer perform multi-eNB synchronization for multicast and broadcast. Instead transmission is on per-cell basis, i.e., when users demand the service serving base stations will not wait for synchronization. A single cell can be managed in a flexible way for broadcast and multicast service and area.

3.4.4 Architecture

Then newly introduced V2X communication architecture has additional exiting entities with corresponding reference points. These are the V2X Control Function (V2X CF), V2X application server, Broadcast and Multicast Service Center(BM-SC) and MBMS-GW.

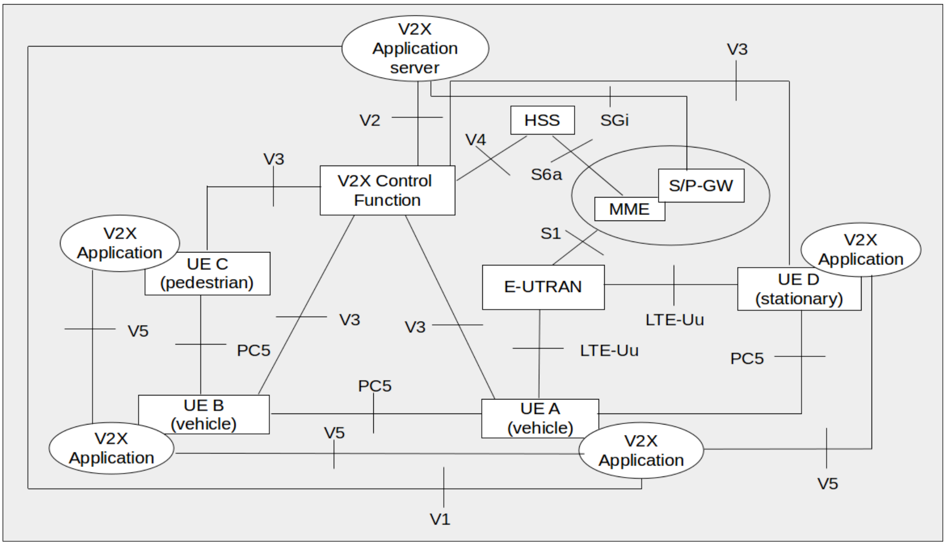


Figure 3.7. V2X architecture

V2X Control Function (V2X CF): In a PLMN there is V2X CF, mostly one unless is needed for load balancing purpose, providing necessary functions to support the service. Its responsibility is to provide PLMN specific parameters for UEs to use in the current PLMN and when UEs are not served by E-UTRAN. When UE is in coverage, it will reach for V2X CF over discovery procedure. Address of V2X CF can be set in UE in IP form of FQDN. If FQDN is used, UE will need to do DNS look up and use IP to communicate with V2X CF. After the discovery, authorization process will be initiated by UE to get the parameters including authorization information, PLMNs in which the UE is authorized to use MBMS, V2X Application Server address information, and radio parameters with geographical area(s) where the UE needs to use PC5 interface when the UE is not served by E-UTRAN.

V2X Application Server (AS): the application server is responsible for receiving data from UEs and is transmitting it to other UEs via unicast or multicast (MBMS). It also provides ECGI(s) and MBMS SAI(s) to BM-SC, and mapping from geographical location information to appropriate target ECGI(s) or MBMS SAI(s) for broadcast.

BM-SC and MBMS-GW: for implementing eMBMS two additional components, Broadcast and Multicast Service Center(BM-SC) and MBMS-GW, are deployed in the core network. The BM-SC is responsible for the management of the eMBMS service-related information, e.g., mapping the service information to the QoS parameters. And the MBMS-GWis the element to deliver eMBMS traffic to multiple cell sites.

Refrence points

V1: The reference point between the V2X application in the UE and in the V2X Application Server.

V2: The reference point between the V2X Application Server and the V2X CF in the operator's network. The V2X Application Server may connect to V2X CF belonging to multiple PLMNs.

V3: The reference point between the UE and the V2X CF in UE's home PLMN. It is applicable to both PC5 and LTE-Uu based V2X communication and optionally MBMS and LTE-Uu based V2X communication.

V4: The reference point between the HSS and the V2X CF in the operator's network.

V5: The reference point between the V2X applications in the UEs.

PC5: The reference point between the UEs used for user plane for ProSe Direct Communication for V2X service.

S6a: It enables transfer of subscription and authentication data for authenticating and authorizing user access to the system between MME and HSS, in case of V2X Service S6a is used to download V2X Service related subscription information to MME during E-UTRAN attach procedure or to inform MME subscription information in the HSS has changed.

LTE-Uu: The reference point between the UE and the E-UTRAN.

Chapter 4

Vehicle and Pedestrian Collision Avoidance

V2X safety application are mainly designed to avoid accidents and loss of life of vehicle owners and pedestrians. The majority of annual car accidents can be linked to collisions at intersections. Collision risk warning systems have the potential to reduce the number of vehicle collisions in several scenarios. Moreover, the information shared between UEs(vehicles, RSU and pedestrians), such as position, speed and heading can be used to predict collisions. The information exchange between them can also be applied to distinguish and locate endangered sections of roads, such as slippery road surfaces. ITS has listed different use cases in relation to collision risk warning applications. Across traffic turn is a single scenario where the purpose is to inform approaching vehicles that another vehicle is intended to turn across traffic. The turn can be across oncoming traffic or merge into an existing traffic stream. The driving pattern of the country (i.e., driving on the left or on the right) should also be respected when considering the application. Another application is road hazard warning, which can reduce the risk of accidents caused by an hazardous location. The aim for it is to inform vehicles of any hazardous location either temporary or permanent (i.e. long term). Additionally and importantly, forward collision warning and intersection collision warning are ITS scenarios included in the safety application. While the aim of forward collision warning application is to avoid longitudinal collision, intersection collision warning application is to prevent collision between two vehicles that enter an intersection without due consideration for traffic conditions.

Safety applications are highly useful in avoiding accidents for cases when driver is human or autonomous. They have obvious real-time constraints, as drivers have to be notified before the information is no longer useful. Another main requirement is accuracy in positioning of vehicles on digital maps. The application works using small packet(CAM and DENM) exchange between vehicles on direct or network-based communication mode.

4.1 CAM

CAM is one of the components of the reference architecture defined by the European Telecommunication Standards Institute (ITSI) for transmitting correct and efficient information to nodes participating in V2X networks. It is periodically broadcasted over PC5 reference point for neighboring nodes(i.e., vehicles/pedestrian UEs also referred as ITS stations) and over LTE-Uu reference point to the network. CAM, also known as Basic Safety Message(BSM), represents status of UEs in the network and contains at least the senderâs accurate position, speed, and heading. It also captures other parameters(i.e., vehicle type, size, speed limits and others) and extreme driving events, such as hard accelerations and braking. According to ITSI standards, CAMs are transmitted with a minimum frequency of 1Hz and maximum of 10Hz depending on the movement status of ITS stations. Even though the message size is small (maximum of few hundreds of bytes, i.e., 50 - 300 bytes), increasing the number of participating stations and cellular traffic load on the base station may create congestion. To mitigate the situation, adaptable frequency standard is used conditioning on ITS dynamics: absolute speed change of 0.5mps, position change of four meters and heading change in greater or equal to four degrees. For instance, a vehicle moving on a fixed direction with constant speed of 50kmph will generate CAM with maximum intergeneration time of 288ms. Additional requirement of the standard is reception latency which should be low with a maximum of 100ms for all CAM based use cases.

4.1.1 CAM generation algorithm

The first type of CAM generation (Algorithm 1) is simple. In every 100ms all the necessary information about the vehicle is collected and is transmitted.

Algorithm 1 CAM generation 1

In every *100ms* :
1: Get *new*`{position, speed, heading, mandatory, optionals}`
2: Send *new*

The second CAM generation algorithm (Algorithm 2) works with time frequency of minimum *tCheckCamGen* seconds. *tCheckCamGen* is a constant time which the vehicle dynamics is checked for pre-generation conditions, and must not exceed the minimum inter-generation time(100ms). When *tCheckCamGen* expires, the latest and basic status of the vehicle will be captured (line 1). Then *tCamGenMax* is checked and if the maximum CAM generation time is reached (line 2), some mandatory and optional informations will be captured for transmission (line 3). Then CAM will be generated (line 4) and latest status of vehicle is saved for later generation (line 5). Otherwise (line 6), if *tCheckCamGen* does not expire, dynamics of the vehicle is checked (line 8). If the absolute difference between old vehicle status and new vehicle status is above one of the thresholds, depending on the type of of service requirement some mandatory and optional informations will be included in the CAM and will be encoded (line 9). Finally, CAM will be transmitted over over the channel (line 10). In line 11, it is necessary to save latest status of the vehicle for later comparison since it will be required for next CAM generation, such as line 8.

Algorithm 2 CAM generation 2

In every *tCheckCamGen* :

1: Get *new*`{position, speed, heading}`
2: **if** *tCamGenMax* expires **then**
3:     Get *new*`{mandatory, optionals}`
4:     Send *new*
5:     $old = new$
6: **else**
7:     **for** `i` **in** `[position, speed, heading]` **do**
8:         **if** $|new[\texttt{i}] - old[\texttt{i}]| \geq threshold[\texttt{i}]$ **then**
9:             Get *new*`{mandatory, optionals}`
10:             Send *new*
11:             $old = new$
12:             **break**
13:         **end if**
14:     **end for**
15: **end if**

4.2 DENM

ITSI has defined the decentralized environmental notification(DEN) basic service that supports various road safety application which are mainly for event-based use cases to alert road users. This kind of message is triggered based on an event either from a station notified by CAM from other vehicles which in this case the station will take effort to evaluate the relevance of information, or from sensors on the station itself. Up on detection of an event, for instance collision risk, ITS stations will broadcast Decentralized Environmental Notification Messages(DENM) over PC5 reference point if communication is direct, or base stations will multicast DENM over LTE-Uu reference point to concerned nodes within the relevance area if communication is network-based. It is also transmitted persistently in a certain frequency until the event is clear. DENM receiver station will act accordingly based on the type of application. For instance, in a collision detection application, when DENM is received on vehicles from the application server vehicles can break immediately. Depending on application requirement and deployment requirement, DENM can be generated when an event is detected for the first time(new), when new information is available for the same event(update), when termination of event occurs(cancellation) by same ITS-S, and when termination of event occurs(negation) by different ITS-S.

4.3 Collision Detection

Collision detection(CD) based on network infrastructure is more efficient than on direct communication. The main reason behind is line of sight where UEs are unable to detect environment due to obstructions(i.e., buildings and other objects), mainly on intersections. A working collision detection prototype, able to notify UEs before crash and to avoid accident is developed. The algorithm uses state-of-the-art approach in order to make accurate predictions. The overall system runs on V2X application server receiving beacons(CAM) from active UEs to estimate possible point of collision. In the beacons, the latest state of UEs containing information such as position, speed, heading, acceleration, and others is encoded. The server is responsible for decoding the beacons, storing active UE status in to two categories(vehicle and pedestrian list) for later computation, updating status, computing trajectory based on available information, and transmitting alert messages(DENM) to relevant UEs if there exists a risk.

4.3.1 CD application Server

The CD application server has basic operation to perform efficiently. The server is always in listening state waiting for CAM on UDP port. As soon as beacon is received, the first operation is updating its database. On the server there are two lists(data table), one for vehicles and one for pedestrians. Having separate data table is advantageous for a later operation during comparison. On update process, the received beacon will be decoded and added to the right table, i.e., if beacon comes from vehicle update vehicle data table or if it comes from pedestrian update pedestrian data table. This is done if the UE(vehicle or pedestrian) is either transmitting it for the the first time or transmitting it after a stale threshold time. The stale threshold time is the maximum allowed time for UE to be active in the database. If this time is reached before consecutive beacon transmission from UE, it will be removed from the database for reducing later comparison time complexity. However, if UE remains in the data table when it's beacon arrives, the row related to it will be updated. The next operation is comparison. This is the time where the main CD algorithm is pulled. Since we have two types of UE and associated data table, comparison will depend on the type of UE. If the beacon is from a vehicle both UE data tables will be processed for predicting collision. However, if it is from a pedestrian comparison is only between vehicle and pedestrian. Pulling the pedestrian data table is not necessary since there is no collision problem between pedestrians, and this is the benefit of having separate data table for each UE.

4.3.2 CD algorithm

The generic nature of the algorithm (Algorithm 3) supports CD between vehicles as well as vehicle and pedestrian(also cyclists). As an input the algorithm requires position, speed and heading as a basis. In addition a dataset to store and update all active UEs is prearranged in the server (first line). The algorithm is processed on the server for each beacon generated by UE. The single beacon representing UE is matched as a pair with each UE in list of active UEs iteratively(line 3). Line 1 and line 2 represent dataset to save colliding UEs after detection and future position of UE (current beacon generator), respectively. In line 4, future position of the other UE in the list is computed based on current position and current velocity. After this, we will need to find the minimum distance between the two UEs and the time when this minimum distance is reached. In line 5, the distance between those two is computed and to simplify computation(line 6) its square is computed. Line 7 is the time instant when the two UEs are closest to each other. If the the closest distance between the two is not in the future or greater than time to collision threshold(line 8) it will be ignored(line 9). Otherwise, the distance will be popped(line 10) and will be matched against space to collision threshold(line 12). If the distance is considered as a risk the UE will be on collision subset for alert(line 13).

Algorithm 3 Collision detection

Require: $\vec{x_0}, \vec{v}, \mathcal{B}$

$\mathcal{C} \leftarrow \emptyset$

$\vec{x}(t) \leftarrow \vec{x_0} + \vec{v}t$

for all $b \in \mathcal{B}$ **do**

  $\vec{x^b}(t) \leftarrow \vec{x_0^b} + \vec{v^b} \cdot t$

  $\vec{d}(t) \leftarrow \vec{x}(t) - \vec{x^b}(t)$

  $D(t) := |\vec{d}(t)|^2 \leftarrow (\vec{v}-\vec{v^b})\cdot(\vec{v}-\vec{v^b})t^2+2(\vec{x_0}-\vec{x_0^b})\cdot(\vec{v}-\vec{v^b})t+(\vec{x_0}-\vec{x_0^b})\cdot(\vec{x_0}-\vec{x_0^b})$

  $t^\star := t\colon \frac{\mathrm{d}}{\mathrm{d}t}D(t) = 0 \leftarrow \frac{-(\vec{x_0}-\vec{x_0^b})\cdot(\vec{v}-\vec{v^b})}{|\vec{v}-\vec{v^b}|^2}$

  if $t^\star < 0$ **or** $t^\star > t2c_t$ **then**

    continue

  end if

  $d^\star \leftarrow \sqrt{D(t^\star)}$

  if $d^\star \leq s2c_t$ **then**

    $\mathcal{C} \leftarrow \mathcal{C} \cup \{b\}$

  end if

end for

return $\mathcal{C}$

The CD algorithm with acceleration (Algorithm 4) has minor difference from the previous algorithm (Algorithm 3). In Algorithm 4 we consider the reported acceleration from the beacon for collision prediction. As a result of this modification in predicting future position, computation becomes more complex to find the time when the two vehicles have the smallest relative distance. Instead of having one time instance quickly, up to three time instances are possible. Hence, each of them must be checked and an alert should be transmitted immediately if one of the time instances meet the condition.

Algorithm 4 Collision detection (with acceleration) pseudocode

Require: $\vec{p}_0, \vec{v}, \vec{a}, \mathcal{B}$

$C \leftarrow \emptyset$

$p_x(t) \leftarrow p_x^0 + v_x t + \frac{1}{2} a_x t^2$

$p_y(t) \leftarrow p_y^0 + v_y t + \frac{1}{2} a_y t^2$

for all $b \in \mathcal{B}$ **do**

  read $\vec{\tilde{p}}^0, \vec{\tilde{v}}, \vec{\tilde{a}}$ from b

  $\tilde{p}_x(t) \leftarrow \tilde{p}_x^0 + \tilde{v}_x t + \frac{1}{2} \tilde{a}_x t^2$

  $\tilde{p}_y(t) \leftarrow \tilde{p}_y^0 + \tilde{v}_y t + \frac{1}{2} \tilde{a}_y t^2$

  $$D(t) \leftarrow (p_x - \tilde{p}_x)^2 + (p_y - \tilde{p}_y)^2 = \\ = \left[p_x^0 - \tilde{p}_x^0 + (v_x - \tilde{v}_x)\, t + \frac{1}{2}\,(a_x - \tilde{a}_x)\, t^2\right]^2 + \\ + \left[p_y^0 - \tilde{p}_y^0 + (v_y - \tilde{v}_y)\, t + \frac{1}{2}\,(a_y - \tilde{a}_y)\, t^2\right]^2$$

  $\mathcal{T} \leftarrow t \colon \frac{\mathrm{d}}{\mathrm{d}t} D(t) = 0$

  for all $t^\star \in \mathcal{T}$ **do**

    if $t^\star < 0$ **or** $t^\star > t2c_t$ **then**

      continue

    end if

    $d^\star \leftarrow \sqrt{D(t^\star)}$

    if $d^\star \leq s2c_t$ **then**

      $C \leftarrow C \cup \{b\}$

      break

    end if

  end for

end for

return $\mathcal{C}$

4.3.3 Thresholds

Transmission of alerts from the server considers two most important threshold values which determine the performance of the system; they are space-to-collision(S2C) and time-to-collision(T2C). These thresholds are different for both collision types: car-car and car-pedestrian. Having different thresholds based on collision type gives advantage over the performance of the CD system. The value of these thresholds directly affects number of false positives and false negatives.

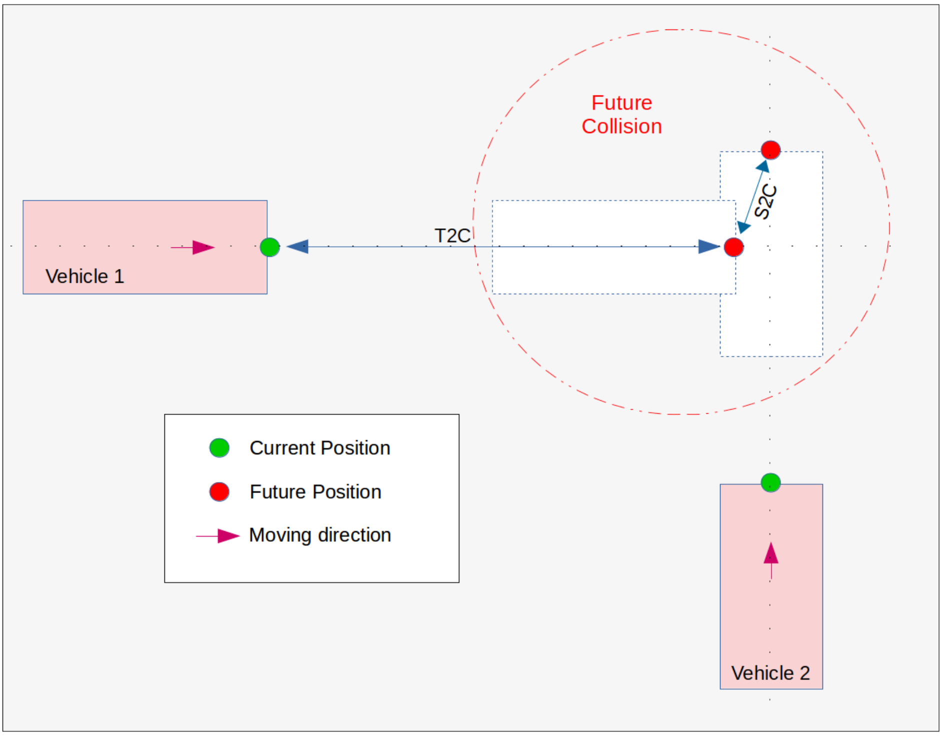


Figure 4.1. T2C and S2C

Space to collision(S2C)

The algorithm represents UEs position in x-axis and y-axis plane as a single point regardless of shape and size of UE. This single point is center of the front bumper for vehicles and pedestrians (considered as vehicles with dimension and speed of human for testing). S2C is the minimum distance between the two points representing UEs on the road map. In the algorithm when warning alert is sent to UEs in risk, S2C_threshold value is used as a final filter. If this value is larger, most scenarios(i.e., vehicles approaching each other on the intersection) will be receiving false positive alerts. On the other side, if this threshold is very small, performance will degrade due to false negatives which are real collisions but undetected by the system. In order to estimate a threshold value close to optimum, empirical test is performed. For instance, between autonomous vehicles with speed of 50kmph(13.89mps), dimension 4.3m*1.8m, the optimum S2C_threshold is value 3.7m. However, between a vehicle and a pedestrian(speed 2mps, dimension 0.4m*0.2m), the threshold is 1.4m. Clearly the size of UE matter in setting S2C_threshold. The picture below describes space on collision effect for different vehicle size. In the worst case (when the distance between the two points is large) collision scenario, for car length of 4.1m and another car length 4.3m, the space on collision is 5.08m and 5.2m, respectively.

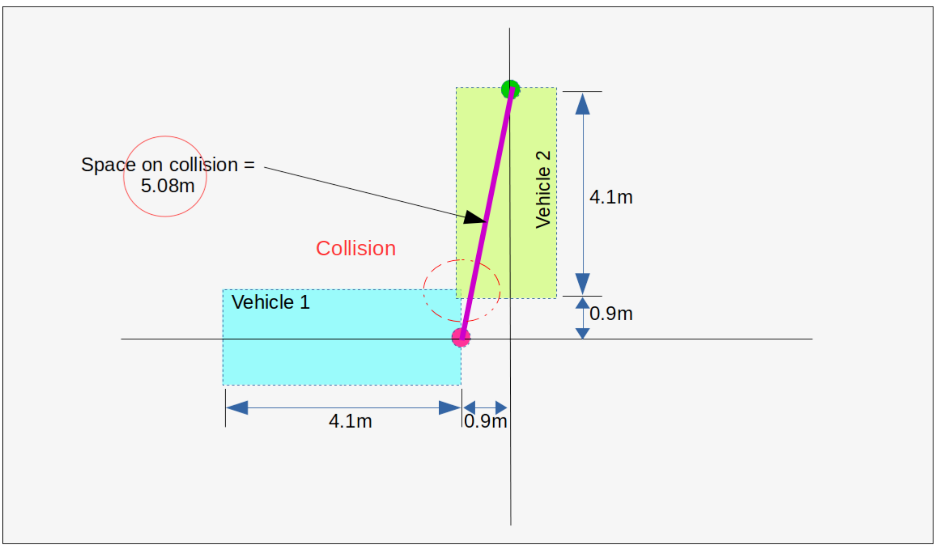


Figure 4.2. Smaller vehicle length

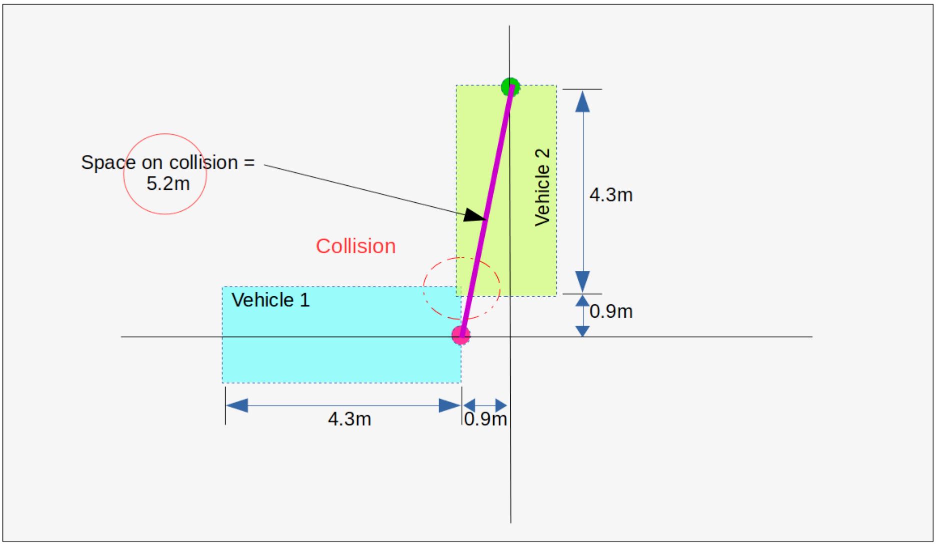


Figure 4.3. Larger vehicle length

Time to collision(T2C)

T2C is the time between now(algorithm is running) and the time when the two points(that are representing UEs) are closest to each other, i.e., S2C is . T2C also means the time before collision for UE to receive the first warning alert. Independently from S2C, T2C_threshold should be set to a meaningful value considering speed of the vehicle. The speed, apparently, affects the breaking time for the vehicle and determines the maximum CAM inter-generation time(e.g. move from below...). Between time of collision and time of detection, collision handling time that considers breaking time, transmission time, maximum CAM inter-generation time, elaboration time(i.e., HMI processing time), human reaction time(if driver is human) and safe marginal time is necessary. The sum of these times, collision handling time is the best value for setting T2C_threshold. Clearly, if this value is smaller collision will not be avoided in time which is downgrade of performance. On the other side, if this value gets bigger, the performance will not upgrade if not degrade due to unpredictable mobility status of vehicle(change in breaking, accelerating, heading will set different outcome), which leads to having false positives, mainly with human drivers. Presenting this with an example, effect of CAM inter-generation time effect is explained, which has also been proved with simulation.

Scenario 1: CAM inter-generation time between 1Hz and 10Hz

Let two vehicles be going and both getting closer to intersection, first car from west to east and second car from south to north with the same speed of 50kmph(13.89mps). This sets breaking time needed to 0.926s. Let's also consider minimum frequency of CAM inter-generation which is 0.1s according to the standard. The other required time variables are constant and can be set to - elaboration time 0.4s, human reaction time 1s, transmission time 5ms.

t2c_threshold estimation: From the scenario T2C_threshold requires 2.331s with out marginal time. If we set T2C_threshold 2.5s in simulations, it should be sufficient enough to stop the vehicles before collision.

In simulations: setting T2C_threshold 2.35s, first alert was transmitted to UEs between a range of 2.301s and 2.443s before collision. Mathematically, the range should be between 2.212s(late CAM due to CAM generation condition, i.e., 2.5s - 0.288s) and 2.5. This means the simulation performed perfectly as expected.

Efficiency: Breaking before collision to avoid crash requires a time greater than 0.926. Taking first alert from simulation(2.301s-2.443s),

Available braking time = First alert time(2.301s) - transmission time(0.005s) - elaboration time(0.4s) - human reaction time(1s) = 0.896s

Since the available time is less than the breaking time, collision is detected late and it can not be avoided.

Solution: considering CAM inter-generation time 288ms(maximum) in T2C_threshold

t2c_threshold estimation: From the scenario T2C_threshold requires 2.519s with out marginal time. According to our scenario, T2C_threshold becomes 2.669s for simulation to stop vehicles from collision.

Efficiency: Considering mathematically which is worst case, the range should be between 2.381s(2.669s - 0.288s) and 2.669s.

Available braking time = 2.381s(worst first alert time) - 0.005s - 0.4s - 1s = 0.976s

Since the available time is greater than the breaking time, collision is detected in time and it can be avoided.

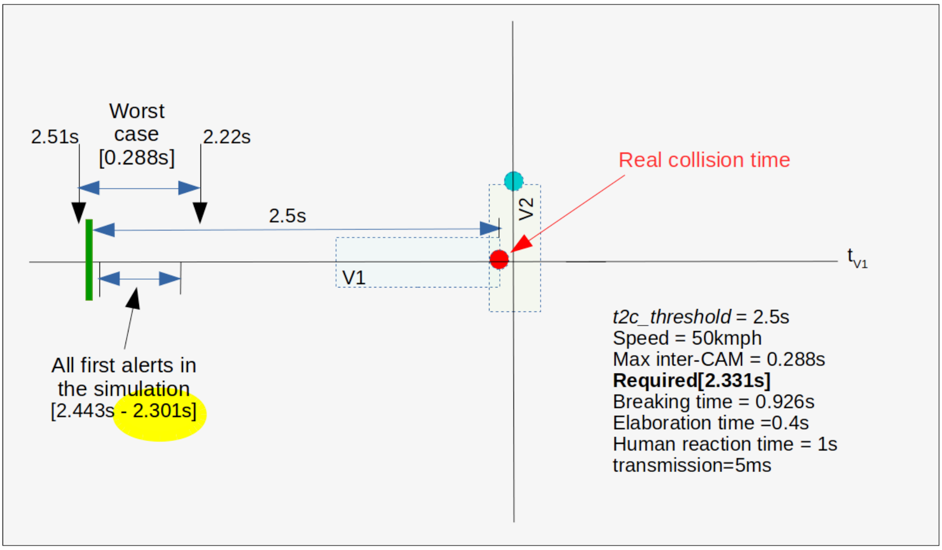


Figure 4.4. CAM generation effect

Chapter 5

Results

5.1 Scenario

5.1.1 Simulation environment

The efficiency of the system was tested based on a given road map considering both vehicles and pedestrians on urban area. For this reason, a road map supporting both entities was needed to to simulated the mobility. The created map has three main bidirectional roads for vehicles: two from south to north, crossing one from east to west. Pedestrians will cross three times over two main streets before reaching to their destination. Thus, on the map there are three vulnerable intersections for car-pedestrian collision and two intersections for vehicle-vehicle. Vehicle and pedestrian route is chosen to create collision on the intersection.

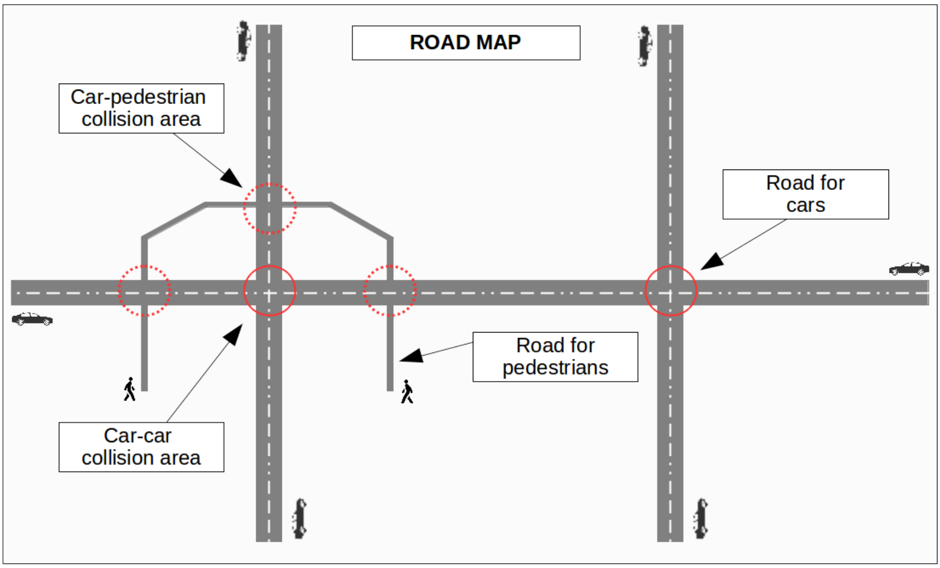


Figure 5.1. Road map

5.1.2 Simulation

Over the road map two types of scenarios were made. The first one is a situation where the vehicle is autonomous, i.e., vehicle will not need human reaction time for taking action(slowing down or breaking) when a hazard is signaled by the network. The other scenario, instead, is vehicle with human driver where responding to hazards takes time. The human response time for all simulation is taken 1s. For each case additional two types of simulations were performed with different CAM generation frequency: constant 1Hz and dynamic ranging between 1Hz to 10Hz.

5.1.3 Mobilty

During mobility, road traffic simulator tool, called SUMO was used in the traffic flow starting from building the road map up to mobilizing vehicles and pedestrians. In order to simulate real scenario, it was necessary to record real collisions from the simulator for later verification. The output of this tool provides detail information for each vehicles and pedestrians such as speed, position, acceleration and others. Other than these, based on the study scenario it is possible to capture different general reports. Among those the one that fits our case is collision on intersection log, which is considered as real collision in real world and it will be matched later with the collision warnings(alerts) transmitted from the network. When the scenario was configured, default settings had to be changed such as the traffic light and deceleration value. On the crossing, priority is always given to pedestrian, i.e, as a pedestrian steps on it vehicles will decelerate to break. This situation by it self removes car-pedestrian collision, and it is against what we are looking for(we are looking for more collisions to observe against the CD algorithm). Deceleration also limits number of collision between car-car as the first car is in the intersection the other will decelerate. As a solution for the issue, deceleration for vehicles has to be 0. The other setting, traffic light order, impacts collision the same way the crossing priority, except the effect is for collisions between vehicles(car-car). What happen with the default is, vehicles will slow down and stop on the traffic line before going through the intersection(collision zone). This is managed with all green traffic light mode. Additionally, the mobility trace for vehicles and pedestrians was made on routes leading to collisions are on intersections only.

Limitation

SUMO is a discreet time simulator and therefore time granularity was required for stepping time. In the experiment, a single simulation runs for 300 seconds with step time of 0.1 second. setting granularity below this value takes very long time to completion. On the other hand setting granularity above this will hide events depending on the mobility speed. For instance, if a vehicle moves 72kmph(20mps), on a granularity of 0.1 second, an event occurred on it for 2.0 meters will be skipped. This will impact the performance of the algorithm in a simulation environment. Proceeding with the example, let's say a collision occurs on the very edge of the cars(worst case) between time $t1$ and $t2$, which is possible. At time $t1$ and $t2$ this collision will not be captured by SUMO. However, the CD algorithm computes the trajectory in continuous time and can capture the collision. Hence, the situation will be alerted to the vehicles but when results are compared it is marked as false positive in the performance metric. The diagrams below show what is explained in the example.

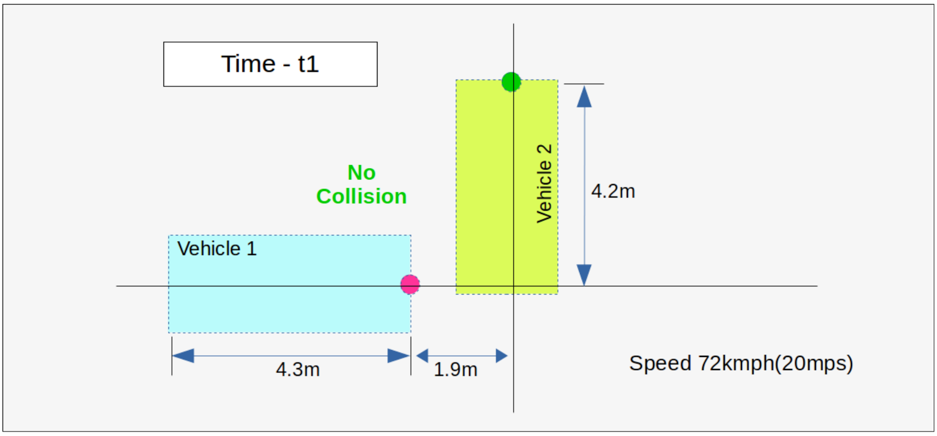


Figure 5.2. SUMO: time - t1

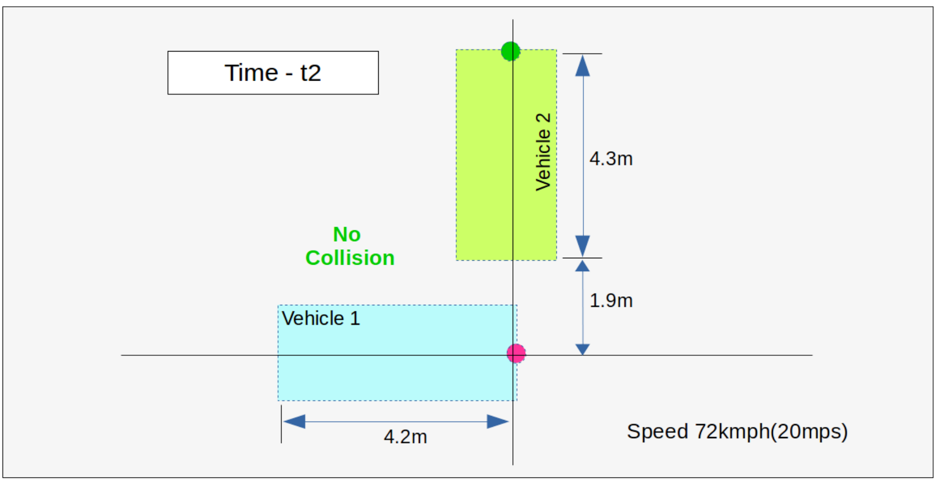


Figure 5.3. SUMO: time - t2

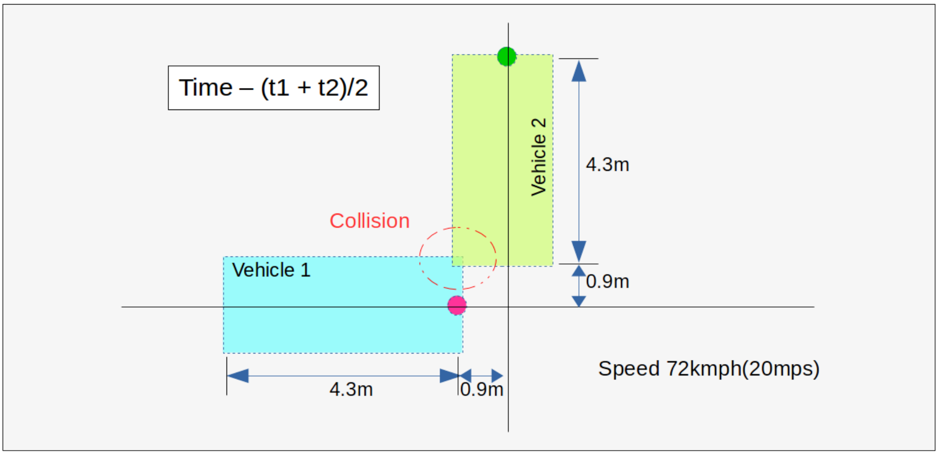


Figure 5.4. SUMO: time - between t1 and t2

5.2 Stability analysis

The experiment started with a stability study on the proposed scenario. In order to model the flow of cars and pedestrians the time between two successive arrival is distributed exponentially, and the arrival of cars and pedestrians is independent from each other. For the overall observation the simulation run for 2000 seconds and the generation time frame was 1500 seconds. According to the result the maximum stability point is when 0.9. If the generation rate of pedestrians increases, rate of cars must decrease to maintain stability. The following table summarized the results.

Pedestrian rate	Max. car rate
0.05	<9.0
0.10	0.85
0.15	0.80
0.20	0.70
0.25	0.50
0.30	0.35
0.35	0.20
0.40	0.10
0.45	0.05
>4.5	No value

Table 5.1. Stablity

Considering one pair of car-pedestrian rate, for instance, it is possible to observe what happens between arrival and departure. In a stable system we expect balance between arrivals when cars are inserted into the system and departures when cars leave the system. Otherwise, if we have more arrivals but less departures, the system will be saturated eventually. With this in mind, for pedestrian arrival rate 0.05 and car rate less than 0.9 we have stable system as we can observe on the graphs. However, for any car generation rate above this point the difference between cumulated arrival and departure grows large with time, and this will lead to instability of the system.

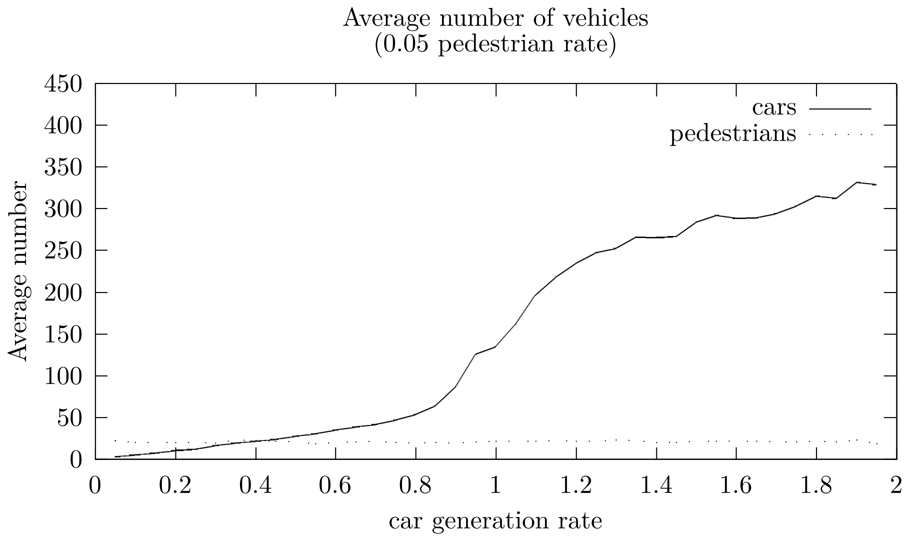


Figure 5.5. Result

In the following supportive graph shows more in detail what is explained above the proportionality between cumulative arrivals and departures fades as cars' rate increase.

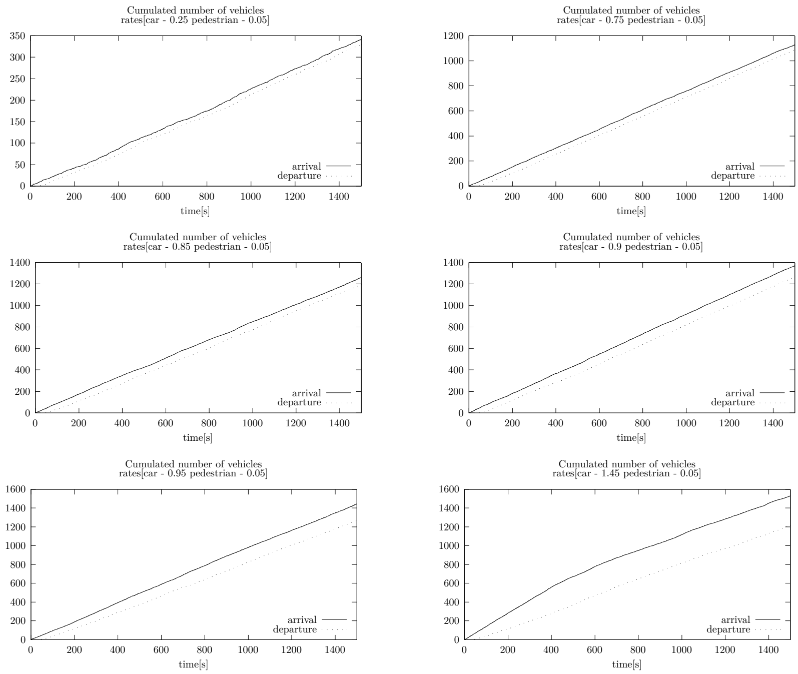


Figure 5.6. Cumulative arrival and departure

5.3 Performance analysis

A collision on the simulation environment can be detected in time, deteted too late and undetected by the algorithm. Moreover the performance metrics can be determined with false negatives and false positives.

Detected in time: collision has been detected by the algorithm and alert is send to cars or pedestrians ahead with sufficent time to react; and accident can be avoided with proper action(breaking in our case).

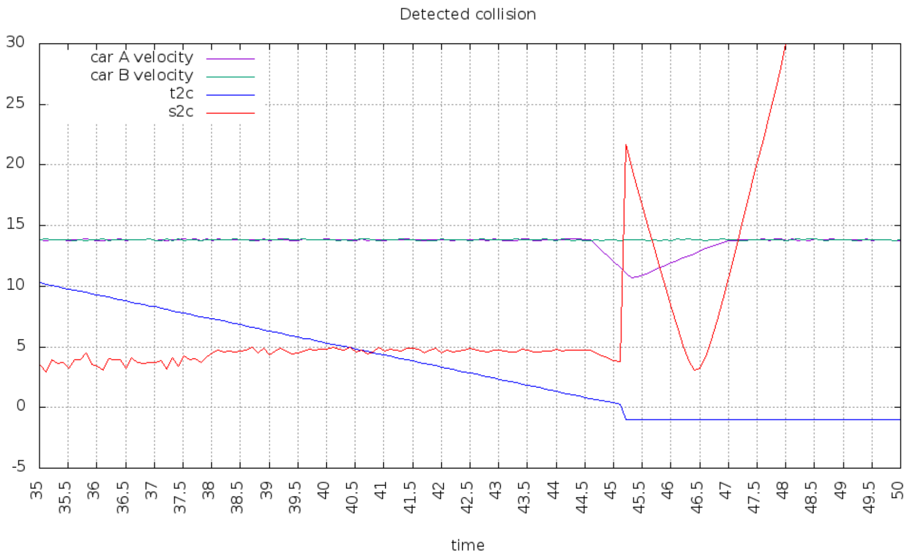


Figure 5.7. Detection on time sample trace

Description: detection in time sample
Considering all the parameters used(shown in table below), there is enough time to avoid collision.

Parameters	value
S2C_threshold(car-car)	5 meters
T2C_threshold(car-car)	10 seconds
Real collision on sumo	45.5s
Collision first detected on server	before 36th second
Alert transmission time	5ms
Processing delay(HMI)	400ms
Human reaction time	1 second
Max. speed(car-A)	50kmph
Max. speed(car-B)	50kmph
Dimention(car-A)	430cm*180cm
Dimention(car-B)	430cm*180cm
Breaking time needed(car-A)	0.9s
Breaking time needed(car-B)	0.9s
Deceleration	Allowed

Table 5.2. Detection on time

Detected too late: collision has been detected by the algorithm and alert is send to cars or pedestrians ahead with insufficient time to react; and accident can not be avoided.

The following figure and table show instance of a collision that is detected late between vehicles.

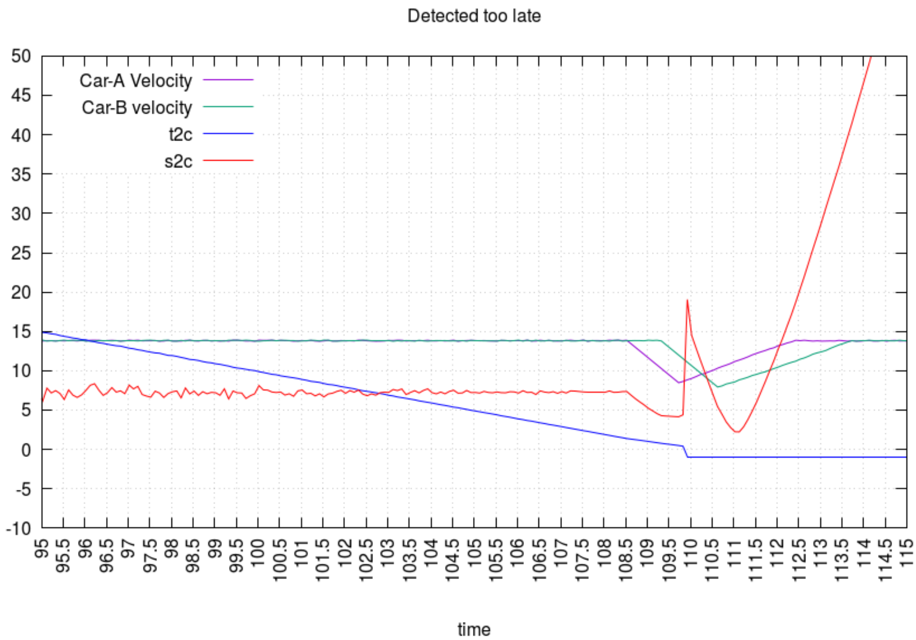


Figure 5.8. Late detection sample trace

Description: late detection sample
Considering all the parameter used (shown in table below), there is no enough time to avoid collision. The reason for this late detection is the speed change of vehicles near the crossing junction.

Parameters	**value**
S2C_threshold(car-car)	5 meters
T2C_threshold(car-car)	10 seconds
Real collision on sumo	110.2s
Collision first detected on server	after 109
Alert transmission time	5ms
Processing delay(HMI)	400ms
Human reaction time	1 second
Max. speed(car-A)	50kmph
Max. speed(car-B)	50kmph
Dimention(car-A)	430cm*180cm
Dimention(car-B)	430cm*180cm
Breaking time needed(car-A)	0.9s
Breaking time needed(car-B)	0.9s
Deceleration	Allowed

Table 5.3. Late detection

Undetected: collision has not been detected by the algorithm and alert can not be triggered; and accident can not be avoided.

False negative: Collision is undetected by the algorithm. However, there is real collision shown on SUMO simulator.

False positive collision is reported to cars or pedestrians. However, there is no real collision shown on SUMO simulator.

Performance analysis was performed based on two CAM scenarios. The first one has a generation frequency of 10HZ while the second one has a reange depending on the dynamics of vehicles, i.e., from 1HZ up to 1HZ.

5.3.1 CAM condition 1

This result is based on CAM generation frequency of 10HZ. Using this configuration on clients (cars and pedestrians), S2C_threshold and T2C_threshold was observed. The test was performed emphatically.

The thresholds are chosen by looking percentage of false negatives and false positives. Out of these two, false negative has full priority over false positives since any real collision must not be missed by any means.

False negatives

In this section different heat-maps for false negatives are shown with description. They are for car-car collision when driver is human, car-car collision when driver is autonomous, and car-pedestrian.

The aim in the following heat maps is to find intersections (S2C-T2C pair of thresholds) that captured all the collisions. This is when the false negative is 0.

Human-driver car: according to the result, the first possible pair is when S2C_threshold is 3.7 and when T2C_threshold is 2.5. Any pair higher than this is a candidate for the selection.

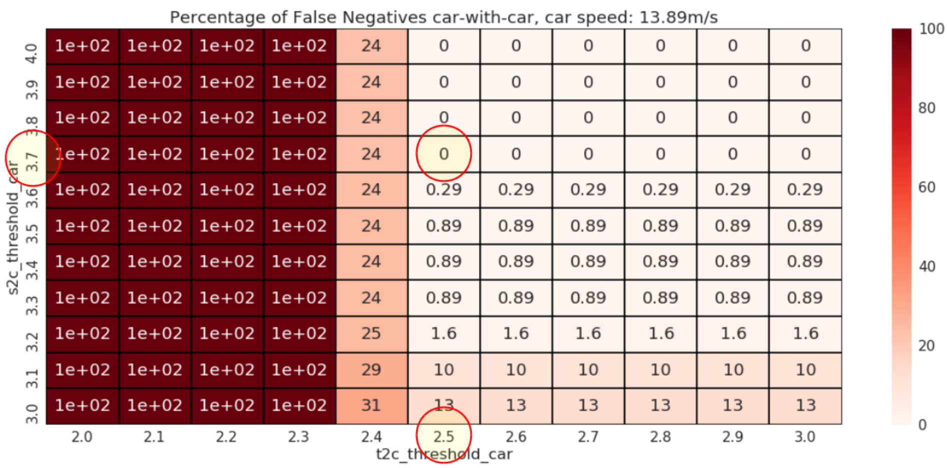


Figure 5.9. False negative: human-driver car

Autonomous car: as we can see, the first acceptable pair is when S2C_threshold is 3.7 and when T2C_threshold is 1.6. Any pair higher than this is a candidate for the selection.

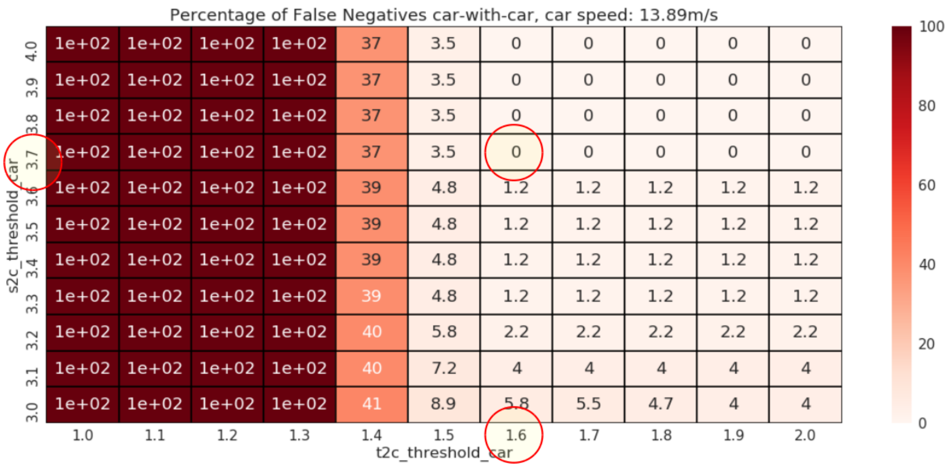


Figure 5.10. False negative: autonomous car

Pedestrian: from the result, the first accepted pair is when S2C_threshold is 1.5 and when T2C_threshold is 0.2. Any pair higher than this is a candidate for the selection. Additionally, when S2C_threshold is 1.4 and when T2C_threshold is 0.9 the percentage of having undetected collision is 0; it is another candidate.

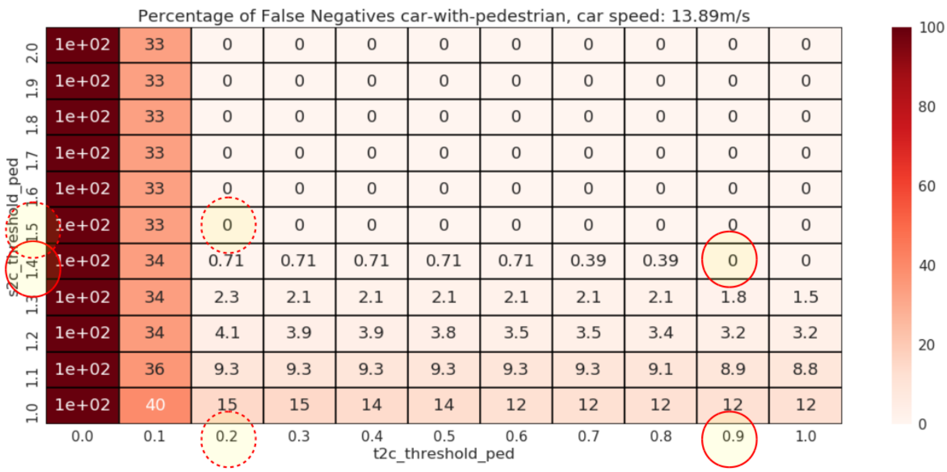


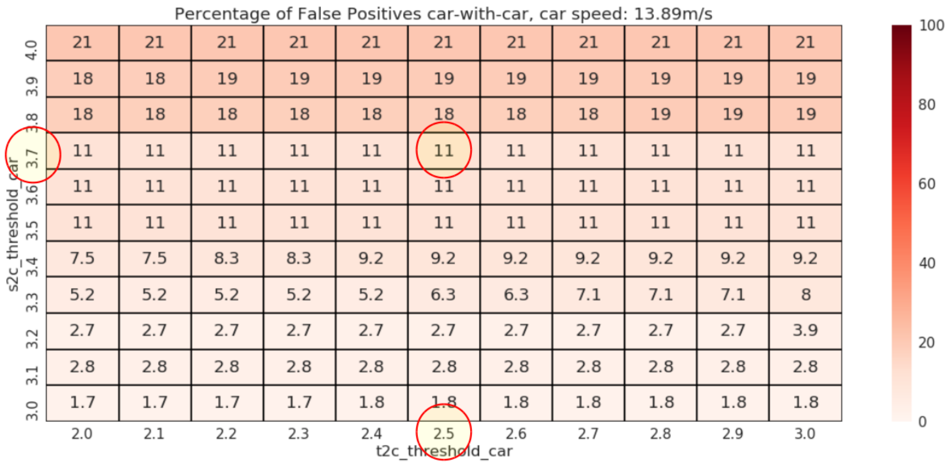
Figure 5.11. False negative: pedestrian

False positives

In this section different heat-maps for false negatives are shown with description. They are for car-car collision when driver is human, car-car collision when driver is autonomous, and car-pedestrian.

The aim in the following heat-maps is to find intersections (S2C-T2C pair of thresholds) that has lowest percentage of false positives. However, there is a catch for it. It must be chosen from the candidates listed in the false negative.

Human-driver car: from the result, the first accepted pair is when S2C_threshold is 3.7 and when T2C_threshold is 2.5. We can not go higher since percentage of false positive will increase, and we can not go lower since we are limited by the false negatives. With this pair the percentage of false positive is 11%.



s2c \ t2c	2.0	2.1	2.2	2.3	2.4	2.5	2.6	2.7	2.8	2.9	3.0
4.0	21	21	21	21	21	21	21	21	21	21	21
3.9	18	18	19	19	19	19	19	19	19	19	19
3.8	18	18	18	18	18	18	18	18	19	19	19
3.7	11	11	11	11	11	11	11	11	11	11	11
3.6	11	11	11	11	11	11	11	11	11	11	11
3.5	11	11	11	11	11	11	11	11	11	11	11
3.4	7.5	7.5	8.3	8.3	9.2	9.2	9.2	9.2	9.2	9.2	9.2
3.3	5.2	5.2	5.2	5.2	5.2	6.3	6.3	7.1	7.1	7.1	8
3.2	2.7	2.7	2.7	2.7	2.7	2.7	2.7	2.7	2.7	2.7	3.9
3.1	2.8	2.8	2.8	2.8	2.8	2.8	2.8	2.8	2.8	2.8	2.8
3.0	1.7	1.7	1.7	1.7	1.8	1.8	1.8	1.8	1.8	1.8	1.8

Figure 5.12. False positive: human-driver car

Autonomous car: from the result, the first candidate pair is when S2C_threshold is 3.7 and when T2C_threshold is 1.6. We can not go higher since percentage of false positive will increase, and we can not go lower since we are limited by the false negatives. With this pair the percentage of false positive is 12%.

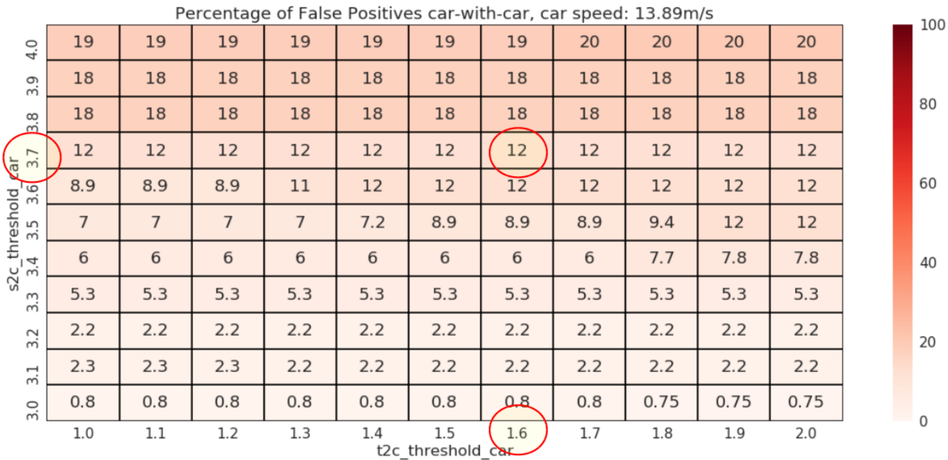


Figure 5.13. False positive: autonomous car

Pedestrian: from the result, the first candidate pair is when S2C_threshold is 1.5 and when T2C_threshold is 0.2. We can not go higher since percentage of false positive will increase, and we can not go lower since we are limited by the false negatives. With this pair the percentage of false positive is 24%.
The other candidate with false negative 0 was S2C_threshold is 1.4 and when T2C_threshold is 0.9. The false positive percentage for this is 21%. For a better performance, apparently, this pair(1.4/0.9) is chosen.

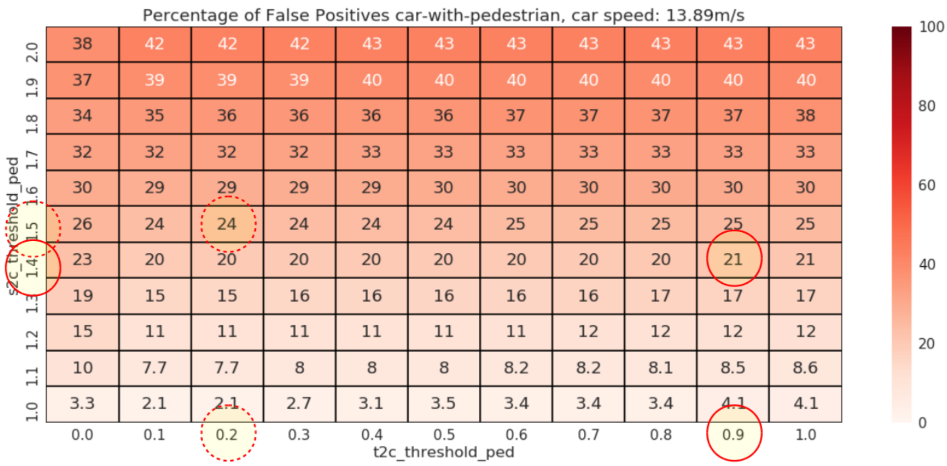


Figure 5.14. False positive: pedestrian

Summary of threshold

The following table shows the summary for the chosen thresholds.

Parameter	**Value**
T2C_threshold(autonomous car)	1.6
S2C_threashold(autonomous car)	3.7
T2C_threashold(human-driver car)	2.5
S2C_threashold(human-driver car)	3.7
S2C_threashold(pedestrian)	1.4
T2C_threashold(pedestrian)	0.9

Table 5.4. S2C - T2C

Simulation result

The following histograms present outcome of the selected thresholds. From the result all collision are detected on time and some false positives are observed. The percentage of false positive is xx for car-car and yy for car-pedestrian collision.

Result 1

Based on the chosen parameters we can look the outcome and it is sufficient for the condition, i.e., all collisions are detected with reduced amount of false positives.

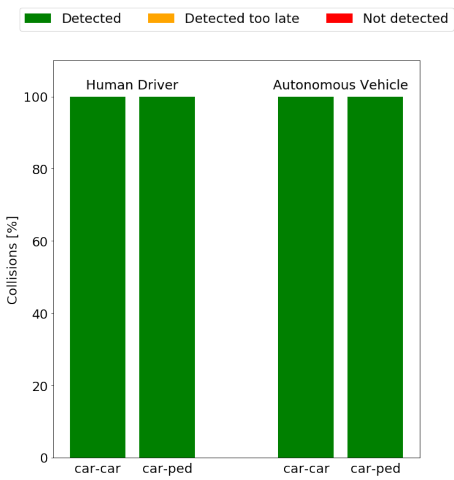


Figure 5.15. false negative: 10Hz CAM frequency

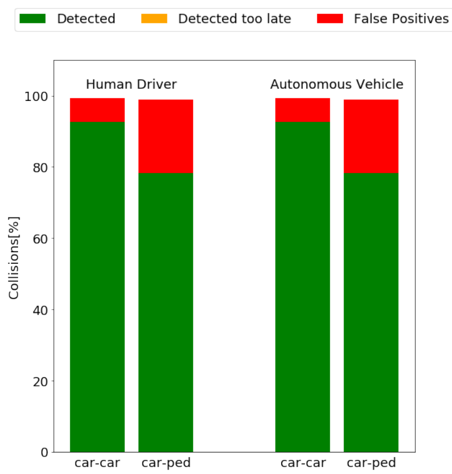


Figure 5.16. false positive: 10Hz CAM frequency

The following is CDF of false positive alerts. According to the result, all alerts reported show very small distance between vehicles and vehicles-and-pedestrians which are less than 1 meter.

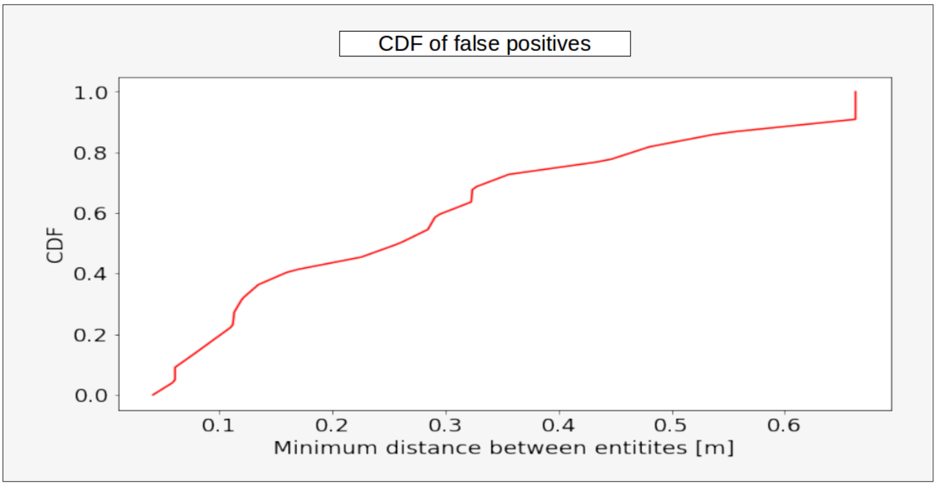


Figure 5.17. CDF

Packet traces

During simulation data and control packets have been traced to observe the channel load both in uplink and downlink. In uplink, the only data packet we have is when CAMs are transmitted. In downlink the data packet is DENM. The control packets that are are captured on the simulator are, on downlink are HARQ, RAC, grant and handover packets. On the other hand in uplink we have feedback control packets besides HARQ and RAC. Before looking channel load of these packet traces the following picture will show number of CAMs in relation to number of UEs.

The generation rate for vehicles is 0.7 and for pedestrian is 0.15. With these pair of rate over the 300 second simulation cars will leave the system very quick and can maintain stability while pedestrians took longer time to leave the system due to their speed. However, in then number of pedestrians in the is still lower than the vehicles. As a result number of CAMs for cars is more than pedestrians. The following illustrates number of CAMs for both cars and pedestrians.

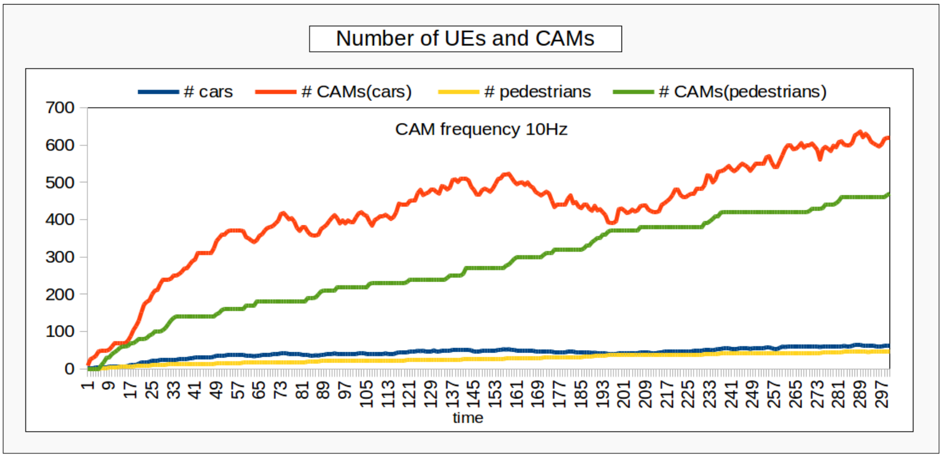


Figure 5.18. Number of UEs and CAMs

Downlink control packet: from the analysis the largest portion of packet trace is from grant and lowest is from handovers. Handovers are broadcasted twice per second and remain unchanged. The main reason for having large number packets from grant is due to the resource scheduling technique used, which is mode 3. The following picture shows control packets transmitted from eNB.

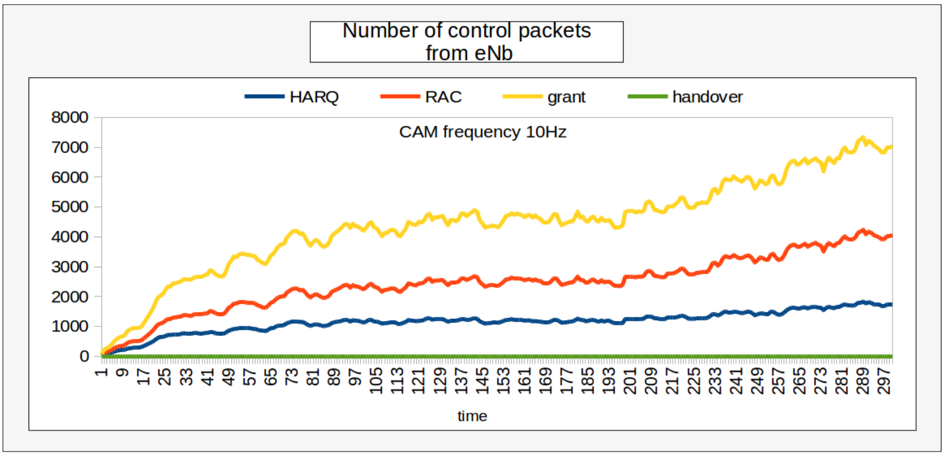


Figure 5.19. Downlink control packets

Uplink control packet: on uplink feedback packets are more frequent than RAC packets. The following picture illustrates number uplink control packets captured in the simulation.

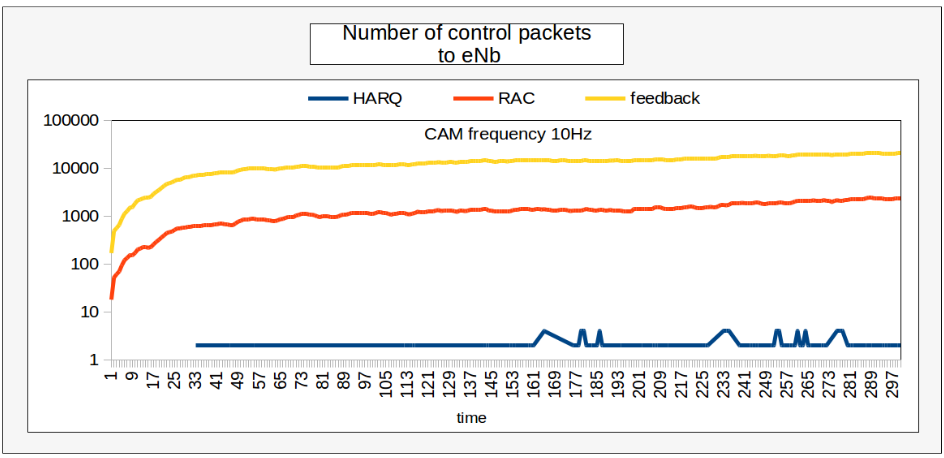


Figure 5.20. Uplink control packets

Packet rate: the following is generalization of data packet and control packets transmitted from/to eNB shown in kilobytes.

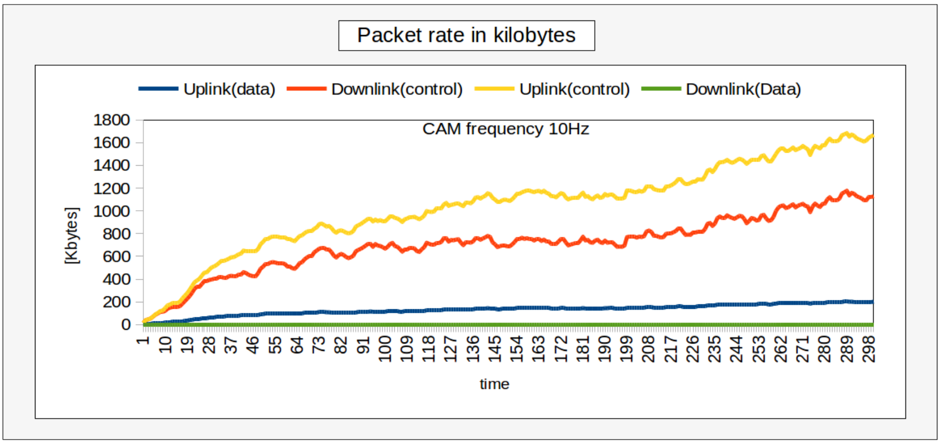


Figure 5.21. Uplink and downlink transmission rate

5.3.2 CAM condition 2

This result is based on CAM generation frequency of range from 1Hz to 10Hz based on vehicle dynamics. Using this configuration on clients, S2C_threshold and T2C_threshold was observed. The test was performed emphatically.

The thresholds are chosen by looking percentage of false negatives and false positives. Out of these two, false negative has full priority over false positives since any real collision must not be missed by any means. Before the threshold analysis, it is useful to see what happens when former thresholds (from CAM condition 1) are used here. The following histograms illustrate the result.

Result 1

Based on the following chosen parameters on the table we can look the outcome and it is not sufficient for the condition.

Parameter	Value
T2C_threashold	2.5
S2C_threashold	3.7
S2C_threashold	1.4
T2C_threashold	0.9

Table 5.5. Parameters for simulation

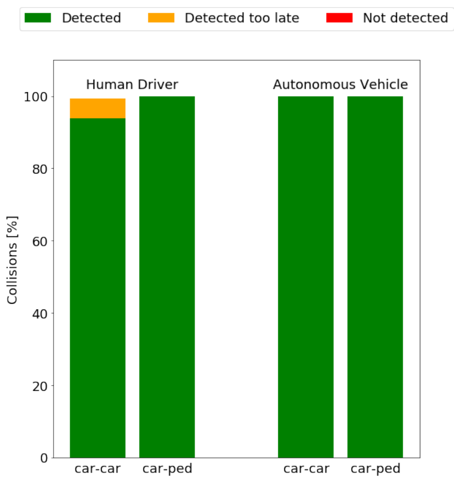


Figure 5.22. false negative: 1Hz - 10Hz CAM frequency

Figure 5.23. false positive: 1Hz - 10Hz CAM frequency

The result shows some collisions that are detected too late. For this reason another threshold analysis is performed to find better thresholds matching the condition.

Like the previous condition, in order to find best pair of thresholds, false positives and false negatives are observed with heat-maps for car-car when driver is human, car-car when driver is autonomous and car-pedestrian collisions.

False negatives

The aim in the following heat-maps is to find intersections (S2C-T2C pair of thresholds) that captured all the collisions as usual. This is when the false negative is 0.

Human-driver car: according to the result, the first possible pair is when S2C_threshold is 3.7 and when T2C_threshold is 2.6. Any pair higher than this is a candidate for the selection.

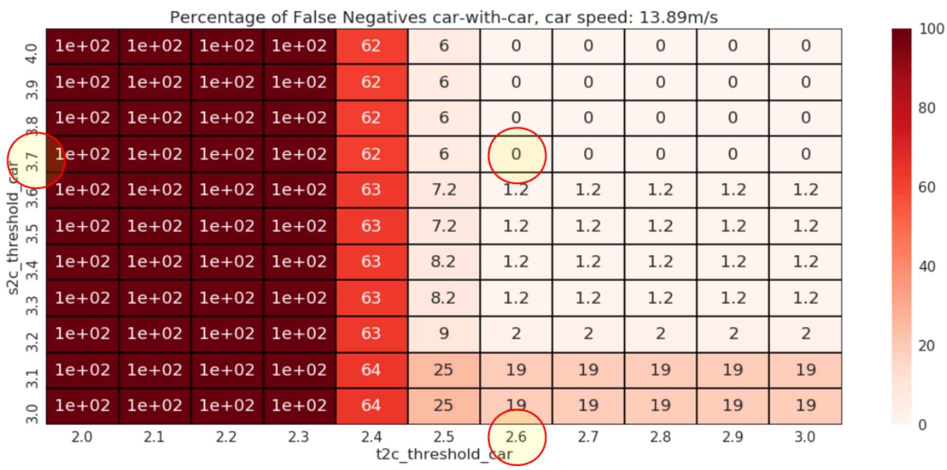


Figure 5.24. False negative: human-driver car

Autonomous car: as we can see, the first acceptable pair is when S2C_threshold is 3.7 and when T2C_threshold is 1.6. Any pair higher than this is a candidate for the selection.

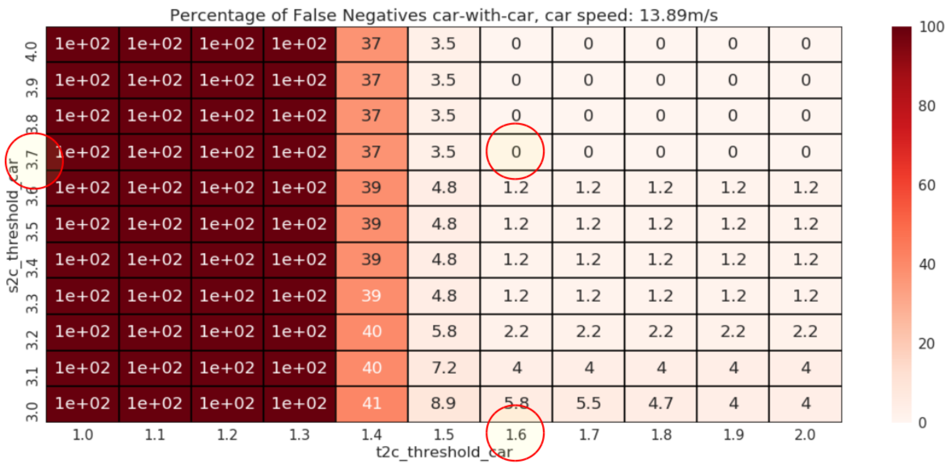


Figure 5.25. False negative: autonomous car

Pedestrian: from the result, the first accepted pair is when S2C_threshold is 1.5 and when T2C_threashold is 0.3. Any pair higher than this is a candidate for the selection.

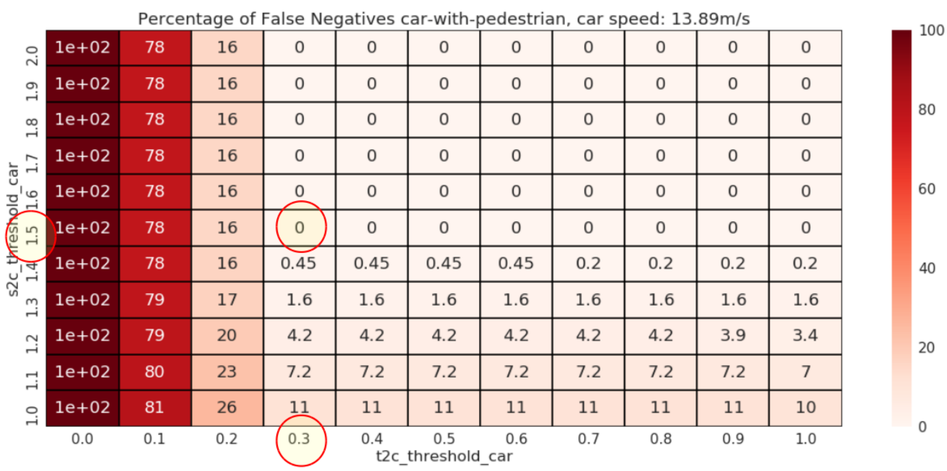


Figure 5.26. False negative: pedestrian

False positives

The goal in the following heat-maps is again to find intersections (S2C-T2C pair of thresholds) that has lowest percentage of false positives.

Human-driver car: from the result, the first accepted pair is when S2C_threshold is 3.7 and when T2C_threshold is 2.6. We can not go higher since percentage of false positive will increase, and we can not go lower since we are limited by the false negatives. With this pair the percentage of false positive is 12%.

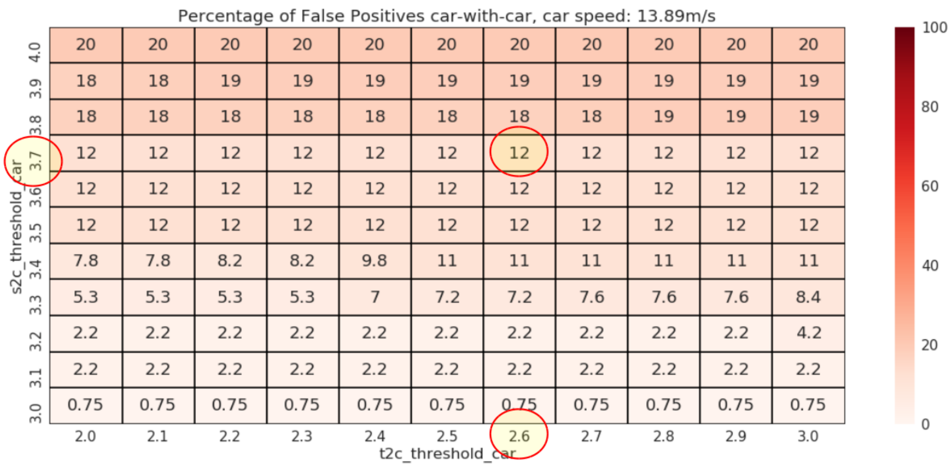


Figure 5.27. False negative: human-driver car

Autonomous car: from the result, the first candidate pair is when S2C_threshold is 3.7 and when T2C_threshold is 1.6. We can not go higher since percentage of false positive will increase, and we can not go lower since we are limited by the false negatives. With this pair the percentage of false positive is 12%.

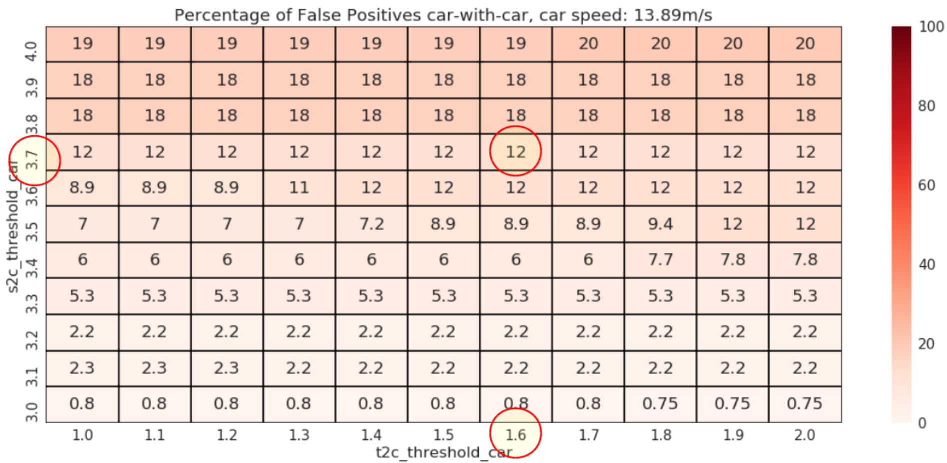


Figure 5.28. False negative: autonomous car

Pedestrian: from the result, the first candidate pair is when S2C_threshold is 1.5 and when T2C_threshold is 0.3. We can not go higher since percentage of false positive will increase, and we can not go lower since we are limited by the false negatives. With this pair the percentage of false positive is 23%.

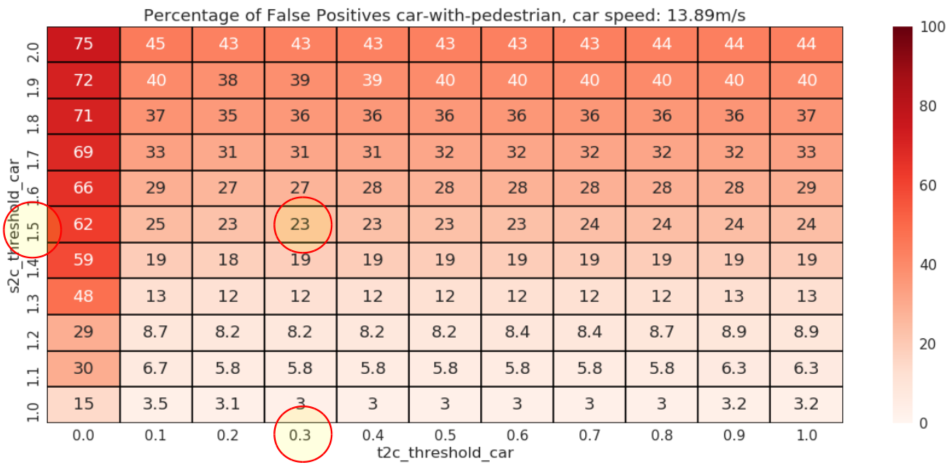


Figure 5.29. False negative: pedestrian

Summary of threshold

The following table shows the summary for the choosen thresholds.

Parameter	**Value**
T2C_threshold(autonomous car)	1.6
S2C_threashold(autonomous car)	3.7
T2C_threashold(human-driver car)	2.6
S2C_threashold(human-driver car)	3.7
S2C_threashold(pedestrian)	1.5
T2C_threashold(pedestrian)	0.3

Table 5.6. S2C - T2C

Simulation result

The following histograms present different outcome of the newly selected thresholds. From the result all collision are detected on time and some false positives are observed. The percentage of false positive is xx for car-car and yy for car-pedestrian collision.

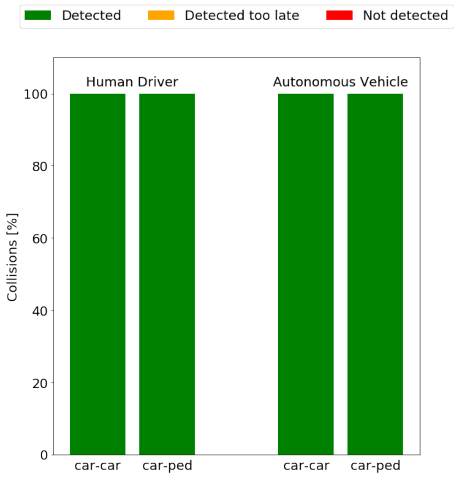


Figure 5.30. false negative: 1Hz - 10Hz CAM frequency

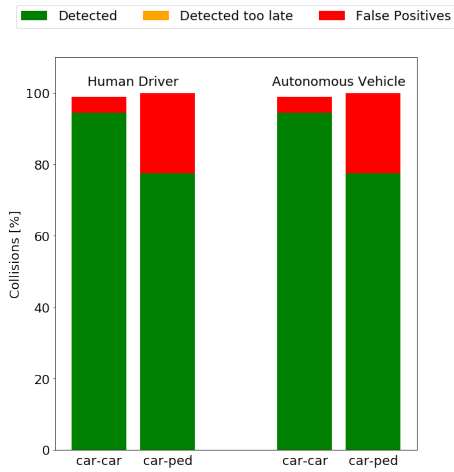


Figure 5.31. false positive: 1Hz - 10Hz CAM frequency

The following is CDF of false positive alerts. According to the result, all alerts reported show very small distance between vehicles and vehicles and pedestrians which are less than 1 meter.

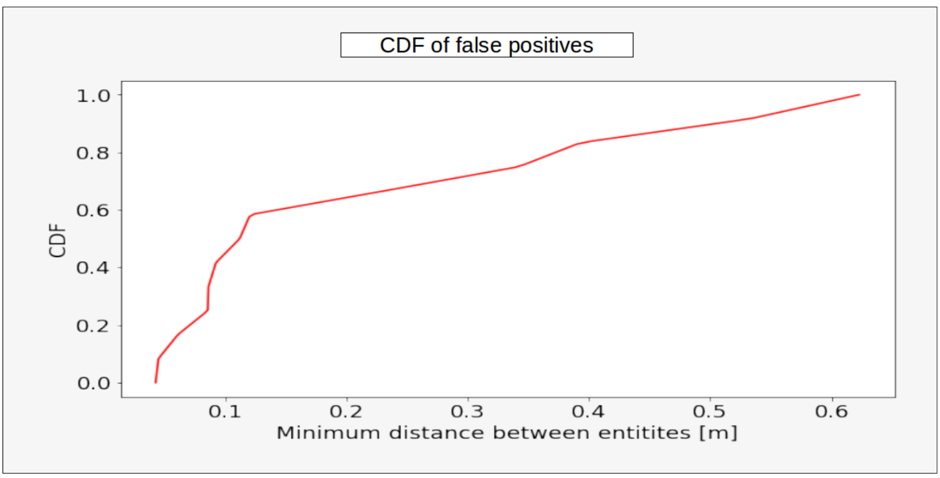


Figure 5.32. CDF

Packet traces

Similar to previous way, data and control packets have been traced to observe the channel load both in uplink and downlink when CAM frequency is from 1Hz to 10Hz. In uplink, the only data packet we have is when CAMs are transmitted. In downlink the data packet is DENM. The control packets that are are captured on the simulator are, on downlink are HARQ, RAC, grant and handover packets. On the other hand in uplink we have feedback control packets besides HARQ and RAC. Before looking these packet traces the following picture will show number of CAMs in relation to number of UEs.

The difference from the previous condition (CAM condition 1) is number of CAMs generated. Since CAM is generated based on conditions(position, speed and heading), almost one-third of CAMs are reduced for cars. For pedestrians, over the 300 second, number of CAMs is less than 50 per second while it was around 400 for the previous condition. The following illustrates number of CAMs for both cars and pedestrians.

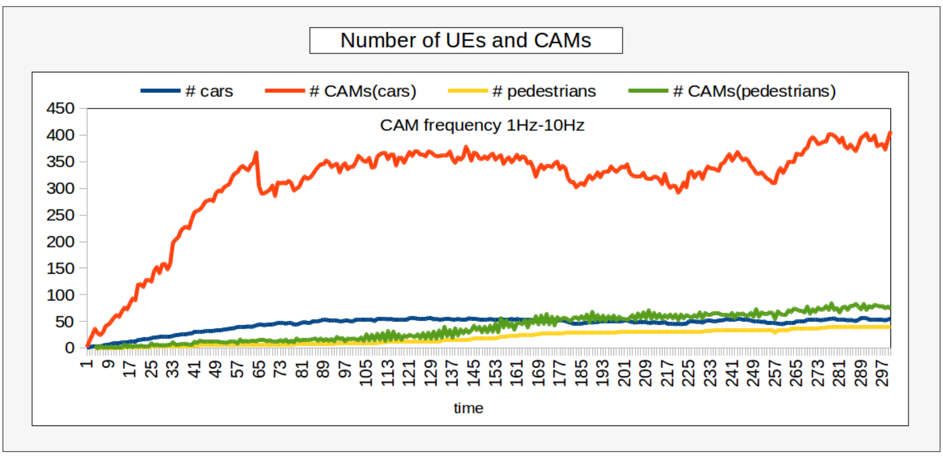


Figure 5.33. Number of UEs and CAMs

Downlink control packet: similarly for downlink control packets the numbers has increased as a result of having smaller number of CAMs.The following picture shows control packets transmitted from eNB.

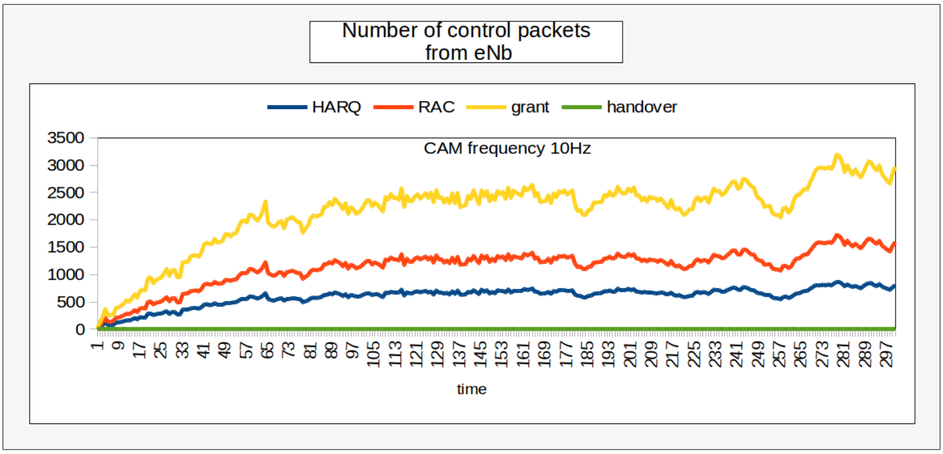


Figure 5.34. Downlink control packets

Uplink control packet: on uplink feedback packets are more frequent than RAC. The following picture illustrates number uplink control packets captured in the simulation.

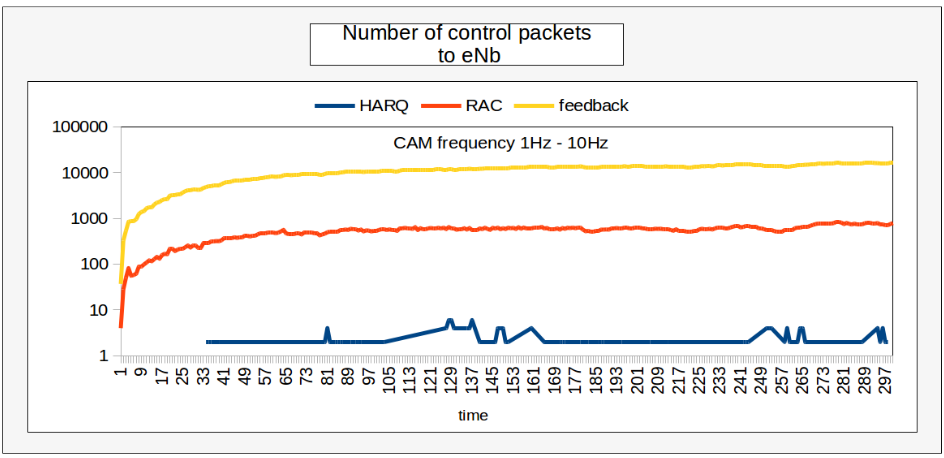


Figure 5.35. Uplink control packets

Packet rate: the following is generalization of data packet and control packets transmitted from/to eNB shown in kilobytes.

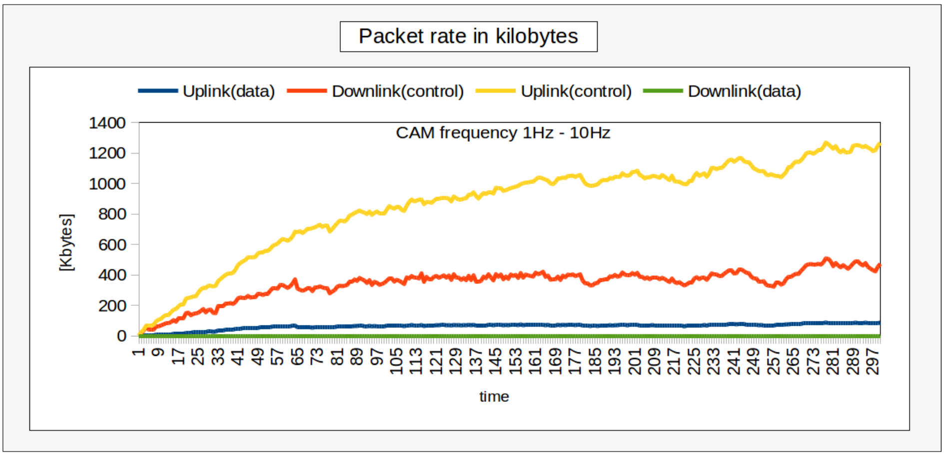


Figure 5.36. Uplink and downlink transmission rate

Chapter 6

Conclusion

This work has been about cellular based V2X communication aimed at supporting safety service to avoid collisions on intersections due to line of sight limitation. Thus, a first prototype has been developed and analyzed for best performance. To build and model a realistic scenario a road traffic simulator involving cars and pedestrians and a communication simulator considering a single cell were used in combination.

On the setup, clients (cars and pedestrians) will transmit their status encoded in CAM through an eNB with a given frequency towards an application server which provides collision detection service. The CAM transmission frequency was configured on the clients in two ways: either fixed at 10Hz which is the maximum frequency in the ETSI standard or ranging from 1Hz to 10Hz depending on their dynamics (i.e., change of speed, position and heading). Once the server acquires the CAMs it is responsible for predicting and notifying future events threatening vulnerable users. These notifications which are encoded through DENM should be delivered in due time giving clients sufficient margin to respond and avoid the collision. This is controlled with the time to collision threshold. The efficiency also relies on another threshold that is the space to collision. This threshold controls number of false positives and false negatives. On the simulation environment it was possible to reach so far as a result 0% false negative and around 11% false positives (including road traffic simulator limitation). All the false positive reports show the distance between the two colliding entities was always less than one meter.

As a result, the first collision detection prototype promises to be highly efficient for safety of users on intersections. It can be extended further considering more scenarios of collision risks involving traffic flows such as across traffic turn. In addition, the prototype can contribute to the development of autonomous vehicles which require ultra reliable and low latency communication.

Appendix A

Appendix

A.1 Server

In the simulation the server is CD application server which can be located either in the cloud or in the mobile operator network. For simulation this is represented in delay as follows.

Location	**Delay**
Cloud	20ms
Mobile operator network	5ms

Table A.1. delay between eNB and application server

A.1.1 DENM format

The following are DENM fields and their desciption which are used in the prototype. The fields are variables and their data format is expressed based on C++ implementation.

Fields	Description
protocolVersion	Not used.
messageId	Not used.
generationTime	Current time for alert generation for transmission. Type is simtime_t(*omnet)
originatorID	Not used.
seqNumber	Not used.
dataVersion	Not used.
expiryTime	simetime_t
frequency	Not used.
reliability	Not used.
isNegation	Not used.
causeCode	Not used.
subCauseCode	Not used.
other_type	Not used.
collision_type	Can be intersection(i.e., car-car, car-ped). Type is string format
longitude	Not used.
latitude	Not used.
alitude	Not used.
t2c	Time to collision. Type is double format
s2c	Space to collision. Type is double format
trust	Not used.

Table A.2. DENM fields

A.2 Clients

In the prototype and simulation clients are either vehicles or pedestrians.

A.2.1 Client type

In the simulation there are only two types of clients.

Type	Value
Car	0
Pedestrian	1

Table A.3. Client type

A.2.2 Client dimention

The following dimentions are taken from SUMO traffic simulator default parameters.

Fields	**Value**
Car length	430cm
Car width	180cm
Pedestrian length	20cm
Pedestrian width	40cm

Table A.4. Client dimention

A.2.3 CAM format

The following are CAM fields and their desciption which are used in the prototype. The fields are variables and their data format is expressed based on C++ implementation.

Fields	Description
carID	Unique integer ID to represent a client(all clients/UEs are cars with different parameters) in the network
type	Type of UE(i.e., type 0 - car and type 1 pedestrian) in integer format
IDframe	CAM ID for the client in the network. An integer increamenting after sending a CAM
msgCount	Not used
posx	Position of a client on the x-axis. Type is double format.
posy	Position of a client on the y-axis. Type is double format.
posz	Not used.
accuracy	Not used
vx	Velocity of a client on the x-axis. Type is double format.
vy	Velocity of a client on the y-axis. Type is double format.
heading	Heading degree angle of the client.
ax	Acceleration of a client on the x-axis. Type is double format.
ay	Acceleration of a client on the y-axis. Type is double format.
bss	Not used.
carLength	Length of a client in cm. Type is integer format
carWidth	Width of a client in cm. Type is integer format
timestamp	Current time for beacon generation for transmission. Type is simtime_t(*omnet)
arrivalTime	

Table A.5. CAM fields

A.2.4 CAM support parameters

For generating CAMs based on the dynamics of clients the following paremeters are involved in the standard(ETSI) and implemented in the prototype.

Fields	Value	Description
T_GenCamMin	100ms	The minimum CAM inter-genertion time
T_GenCamMax	1000ms	The maximim CAM inter-genertion time
T_CheckCamGen	100ms	Client dynamics inter-checking time. It should not exceed T_GenCamMin
N_GenCam	3	Number of consecutive CAMs to be generated when a status(speed, heading and position) of client exceeds threshold

Table A.6. CAM processing parameters

A.2.5 Dynamics threshold

CAM is generated immediately when dynamics of client exceeds these thresholds. The following are taken from the standard(ETSI)

Fields	**Value**
heading	4 degrees
position	4m
velocity	0.5mps

Table A.7. Dynamics threshold

A.3 Configuration

A.3.1 Channel model

Channel model type can be real or dummy. For the simulation type is real.

Parameter	**Value**	**Description**
shadowing	false	Enable/disable shadowing. Type is boolean format.
shadowing-type	LOG_NORMAL	Shadowing type. Type is string format.
scenario	U_MA_CELL	Pathloss scenario from ITU, urban macrocell. Type is string format.
nodeb-height	25m	Height of eNB. Type is double format.
building-height	20m	Height of building. Type is double format.
carrierFrequency	2GHz	Carrier Frequency in GHz. Type is double format.
targetBler	0.001	Target bler used to compute feedback. Type is double format.
harqReduction	0.2	HARQ reduction. Type is double format.
antennaGainUe	0	Antenna Gain of UE. Type is double format.
antennGainEnB	18	Antenna Gain of eNB. Type is double format.
thermalNoise	-104.5	Thermal Noise for 10 MHz of Bandwidth. Type is double format.
ue-noise-figure	7	UE noise figure. Type is double format.
bs-noise-figure	5	eNB noise figure. Type is double format.
fading	false	Enable/disable fading. Type is boolean format.
fading-paths	6	If fading this parameter specify the number of path (tap channel). Type is integer format.
extCell-interference	true	If true, enables the inter-cell interference computation. Type is boolean format.
multiCell-interference	false	If true, enables the multi-cell interference computation. Type is boolean format.

Table A.8. Channel model

Bibliography

[1] 3GPP TS 23.285 V14.2.0: Architecture enhancements for V2X services, May 2017.

[2] 3GPP TS 24.386 V14.2.0: User Equipment (UE) to V2X control function; protocol aspects; Stage 3, October 2017.

[3] 3GPP TS 29.388 V14.0.0: V2X Control Function to Home Subscriber Server (HSS) aspects (V4); Stage 3, May 2017.

[4] 3GPP TS 23.303 V12.2.0: Proximity-based services (ProSe); Stage 2 ; Stage 3, September 2014.

[5] 3GPP TS 22.185 V14.3.0: Service requirements for V2X services, March 2017.

[6] 3GPP TS 36.101 V15.2.0: User Equipment (UE) radio transmission and reception, March 2018.

[7] 3GPP TR 36.785 V14.0.0: Vehicle to Vehicle (V2V) services based on LTE sidelink; User Equipment (UE) radio transmission and reception, October 2016

[8] ETSI EN 302 637-2 V1.3.1: Vehicular Communications; Basic Set of Applications; Part 2: Specification of Cooperative Awareness Basic Service, September 2014.

[9] ETSI EN 302 637-3 V1.2.1: Vehicular Communications; Basic Set of Applications; Part 3: Specifications of Decentralized Environmental Notification Basic Service, September 2014.

[10] ETSI TR 102 638 V1.1.1: Vehicular Communications; Basic Set of Applications; Definitions, June 2009

[11] ETSI TS 136 213 V14.2.0: Evolved Universal Terrestrial Radio Access (E-UTRA); Physical layer procedures, April 2017

[12] 5G Americas, V2X Cellular solution, October 2016

[13] LTE-V for Sidelink 5G V2X Vehicular Communications, Rafael Molina-Masegosa and Javier Gozalvez, October 2017

[14] Vehicle-to-Everything (v2x) Services supported by LTE-based Systems and 5G, Shanzhi Chen, Jinling Hu, Yan Shi, Ying Peng, Jiayi Fang, Rui Zhao, and Li Zhao, June 2017

[15] SC-PTM or MBSFN for Mission Critical Communications, Alaa Daher, Marceau Coupechoux, Philippe Godlewski, Pierre Ngouat and Pierre Minot
[16] www.3gpp.org