THE FUTURE OF THE CONNECTED VEHICLE

A Degree Thesis

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Abstract

Vehicle-to-everything (V2X), including vehicle-to-vehicle (V2V), vehicle-to-pedestrian (V2P), vehicle-to-infrastructure (V2I) and vehicle-to-network (V2N), will improve road safety and traffic efficiency. Two technologies are available to support these applications: IEEE's 802.11p and 3GPP's C-V2X.

The aim of this thesis is to give an opinion on the evolution of the communications between vehicles, especially the ones based on LTE, and to analyze and suggest basic requirements for this technology.

Some assumptions for C-V2X parameters and scenarios has been made to be tested with a program developed with *Matlab*, resulting in delay and capacity recommendations for a proper performance.

After both literature and calculations have been analysed, this document concludes that, although LTE-V2X performs well in low density scenarios, further improvements need to be developed for this technology to be able to support safety-related applications, which is expected to be done by 3GPP's Release 15.

Resum

Les tecnologies de vehicle connectat (V2X), que inclouen la connectivitat entre vehicles (V2V), entre vehicles i vianants (V2P), i entre vehicles i infraestructura (V2I/N), milloraran la seguretat a la carretera i l'eficiència en la gestió del trànsit. Hi ha dos tecnologies proposades: l'IEEE802.p i l'LTE.

L'objectiu d'aquest treball és el de donar una opinió sobre l'evolució de les comunicacions vehiculars, especialment les basades en LTE, i d'analitzar i proposar requeriments per aquesta tecnologia.

S'han assumit diferents escenaris i paràmetres per a ser provats mitjançant un codi programat amb *Matlab,* donant com a resultats uns requeriments de retards i capacitats.

Després d'un anàlisi bibliogràfic i de fer càlculs sobre el model, aquest document conclou que, tot i que l'LTE-V2X és adequat per situacions poc complexes, cal fer encara moltes millores i avenços per poder suportar aplicacions de seguretat per a vehicles, cosa que s'espera que faci el 5G.

Resumen

Las tecnologías de vehículo conectado (V2X), que incluyen la conectividad entre vehículos (V2V), entre vehículos y peatones (V2P), y entre vehículos e infraestructura (V2I/N), mejorarán la seguridad vial i la eficiencia en la gestión del tráfico. Existen dos propuestas: el IEEE802.11p y el LTE.

El objetivo de este trabajo es el de dar una opinión sobre la evolución de las comunicaciones vehiculares, especialmente aquellas basadas en LTE, y de analizar y proponer requerimientos para esta tecnología.

Se han asumido diferentes escenarios y parámetros para ser probados mediante un código programado en *Matlab*, dando como resultado unos requerimientos de retardos y capacidades.

Después de un análisis bibliográfico y de hacer cálculos sobre el modelo, este documento concluye que, a pesar de que el LTE-V2X es adecuado para situaciones poco complejas, hace falta aún muchas mejoras i adelantos para poder soportar aplicaciones de seguridad para vehículos, algo que se espera que haga el 5G.

Acknowledgements

I would first like to thank my thesis advisor Professor Josep Paradells for his patience and steering me in the right direction.

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1. Introduction

The main goal of this thesis is to give an opinion on the evolution of cellular communications between vehicles as well as between vehicles and infrastructure, based on capacity studies and an analysis of the available and future technologies.

To face this challenge, some basic knowledge on cellular networks (especially LTE) was needed, which I had been given by Professor Paradells in *Sistemes de Suport a les Comunicacions Mòbils (SSCMOB)*. However, this had to be expanded through bibliographic research.

Furthermore, to be able to analyze some parameters of V2X and get capacity results, some knowledge on queueing theory in communications was also needed. The details of the calculations involved in an M/G/1 queue were explained by Professor De la Cruz in the subject *Anàlisi i Avaluació de Xarxes (AAX)*.

To achieve this objective, the first step was researching the literature available on Vehicle-to-vehicle communications, analyzing these technologies and comparing them to be able to focus only on one. The second step was a study of the proposed technology with the aim of presenting the requirements it should comply to function properly, especially its capacity. The main tool used to calculate these requirements was *Matlab*, with scripts that I wrote. The final stage of the project consisted in summing up the conclusions reached and offering an outlook on how the vehicle connectivity might move forward.

All in all, these process is summarized as follows:

1. **Data gathering:** bibliographic research through the literature mainly available in 3GPP and IEEE digital libraries.
2. **State of the art:** document which presents the technologies involved in vehicle communications.

- ***Deliver State of the art***

3. **In depth research:** once the technology is chosen, a research focusing on the details of its functioning.

- ***Deliver LTE-V2X study***

4. **Study of parameters:** once the technology is studied, choose the parameter(s) to focus on.
5. **Calculations:** write some scripts in *Matlab* to test the methodologies found in the research with the chosen parameters, and get the results.

- ***Deliver Calculations report***

6. **Final report:** summing up all the results and conclusions and formally presenting them.

- ***Deliver Final report***

These tasks and milestones have been represented in the next diagram:

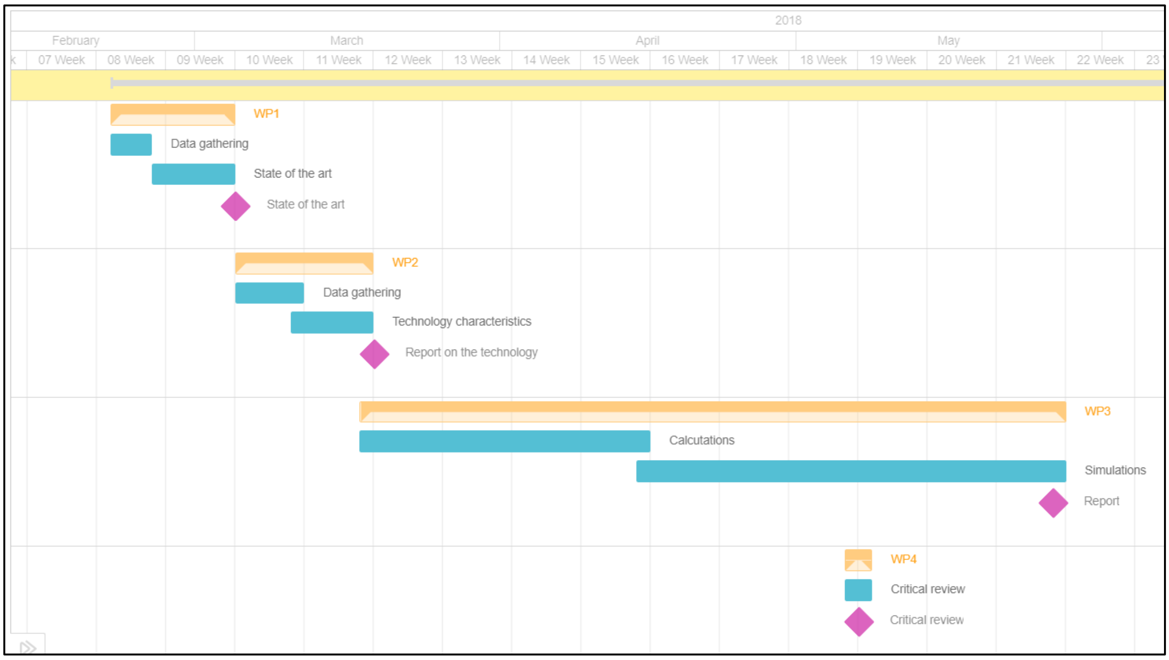

Figure 1. GANTT diagram of the project

No major incidences occurred during the project. The tutor and I have been meeting multiple times a month to review my progress and to discuss which should be the next steps. Nevertheless, this progress might have been slower than it should have, especially when obtaining basic results for some calculations needed. The difficulties in understanding some procedures and calculations have affected the timings in the work plan.

The major change in the work plan was the decision of not attempting to do simulations, which was a milestone included in the initial project plan. This was due to the hardware and software difficulties we might had had to face. As the majority of the results we could get through calculations could be quite close to the reality, simulations were not needed for the goals of this project.

In spite of the fact that the communication between me and the tutor was fluid via email during the project, in May it was not, which led to not meeting for a month. Some doubts could not be solved and the progress was inevitably slowed down.

Lastly, the dedication might not have been enough to fulfill the expectations of the project. Besides, the hours invested are not clearly reflected in the results, due to difficulties with understanding some concepts and with scheduling.

2. State of the art

2.1. Introduction

Nowadays, the first generations of sensor-assisted vehicles are already taking the streets. In spite of their capacity of handling an increasing number of road scenarios, the need to extend perceptual bounds beyond the scope of the individual vehicle has become significant. Therefore, the vehicle-to-everything communication is emerging.

Many possible benefits, such as a drastic decrease in traffic-related fatalities, reduced logical costs for vehicular fleets operation, the introduction of new business models… have attracted a lot of players' interest in Intelligent Transportation Systems (ITS).

Research regarding ITS communications has been aimed at supporting applications ranging from fully autonomous vehicle operation and essential road-safety support to traffic flow optimization and in-car infotainment services. The various forms of ITS communication, commonly referred as *vehicle to everything*, are:

- Vehicle to vehicle (V2V)
- Vehicle to infrastructure (V2I) or network (V2N)
- Vehicle to pedestrian (V2P)

A lot of discussions of V2X communications envision the use of dedicated short-range communications (DSRC), supported by the IEEE 802.11p standard. This standard for wireless communication is supplemented by the IEEE 1609 family of standards, including definitions of the architecture, management structure, security, and physical access for wireless vehicular networks, referred to collectively as WAVE (Wireless Access in Vehicular Environments). The communication occurs between a wireless transmitter on the vehicle (On-Board Units, OBUs) and infrastructure Road-Side Units (RSUs). It provides a number of benefits, like low end-to-end latency, flexible organization and relatively low cost, but it has also a number of issues, including service degradation in congested scenarios, security problems and difficulty with compromised line of sight. Although some of these issues might be improved with a robust infrastructure it is not clear whether such infrastructure will be deployed or to what extent.

Another candidate access technology for V2X is the mobile cellular network, often referred to as Cellular V2X (C-V2X), including both current LTE technology and future 5G developments. Compared to DSRC, these technologies offer a number of advantages, including a much larger coverage area, pre-existing infrastructure, deterministic security and QoS guarantees, as well more robust scalability. But such advantages, many a result of a centralized architecture, come at the cost of end-to-end latency, dependence on connectivity with infrastructure, and a higher price for network usage. For V2X applications which are time-sensitive, latency overhead might be a major obstacle. However, the development of a side-link LTE makes progress and its standardization is mature, so implementation in the near term is plausible.

2.2. V2X message types

Defined by ETSI [18], for ITS use cases there are the following message types.

2.2.1. CAMs (Cooperative Awareness Messages)

The Cooperative Awareness (CA) Basic Service provides by means of periodic sending of status data a cooperative awareness to neighboring nodes.

The Cooperative Awareness Messages (CAMs) are distributed within the ITS network and provide information of presence, positions as well as basic status of communicating ITS stations to neighboring ITS stations that are located within a single hop distance. All ITS stations shall be able to generate, send and receive CAMs, as long as they participate in V2X networks. By receiving CAMs, the ITS station is aware of other stations in its neighborhood area as well as their positions, movement, basic attributes and basic sensor information. At receiver side, reasonable efforts can be taken to evaluate the relevance of the messages and the information. This allows ITS stations to get information about its situation and act accordingly.

The Approaching Emergency Vehicle and Slow Vehicle Warning are just two use cases which benefit from CAM.

2.2.2. DENMs (Decentralized Environmental Notification Messages)

The Decentralized Environmental Notification (DEN) Basic Service supports the various Road Hazard Warning (RHW) use cases. A DENM (DEN Message) transmission is triggered by a cooperative RHW use case to provide information about a specific driving environment event or traffic event to other ITS stations. The ITS station that receives the DENM is able to provide appropriate Human Machine Interface (HMI) information to the end user, who makes use of these information or takes actions in its driving and travelling.

Upon detection of an event that corresponds to a RHW use case, the ITS station immediately broadcasts a DENM to other ITS stations located inside a geographical area and which are concerned by the event. The transmission of a DENM is repeated with a certain frequency. This DENM broadcasting persists as long as the event is present.

2.2.3. MAPs (Map data messages)

The RLT (Road and Lane Topology) service is one instantiation of the infrastructure services to manage the generation, transmission and reception of a digital topological map, which defines the topology of an infrastructure area. It includes the lane topology for e.g. vehicles, bicycles, parking, public transportation and the paths for pedestrian crossings and the allowed maneuvers within an intersection area or a road segment. In future enhancements the digital map will include additional topology-descriptions like traffic roundabouts. The area of an intersection described by the topology covers about 200 m of the approaches, starting from the position of the stop line. If a neighbor intersection is closer than 400 m, the description may be done up to an extent of approximately the half distance between the intersections.

The RLT service uses MAPs or MAPEMs (MAP Extended Messages) which represent the topology/geometry of a set of lanes. E.g. considering an intersection MAPEM defines the topology of the lanes or parts of the topology of the lanes identified by the intersection reference identifier. The MAPEM does not change very often in time. The same MAPEM is retransmitted with the same content, unless the Application indicates to transmit a new

MAPEM. If the size of the MAPEM exceeds the allowed message length (e.g. MTU), the RLT service fragments the message which will be transmitted in different messages.

2.2.4. SPaTs (Signal Phase and Timing messages)

The TLM (Traffic Light Maneuver) service is one instantiation of the infrastructure services to manage the generation, transmission and reception of SPAT (and SPATEM, SPATS Extended Messages) messages. The TLM service includes safety-related information for supporting traffic participants (vehicles, pedestrians, etc.) to execute safe maneuvers in an intersection area. The goal is to enter and exit an intersection "conflict area" in a controlled way. The TLM service informs in real-time about the operational states of the traffic light controller, the current signal state, the residual time of the state before changing to the next state, the allowed maneuvers and provides assistance for crossing. Additionally, the TLM service foresees the inclusion of detailed green way advisory information and the status for public transport prioritization.

The TLM service provides real-time information of the traffic light signal phase and timing of an intersection or parts of an intersection identified by the intersection reference identifier. The timestamp indicates the order of messages within the given time. The SPAT is not repeated.

The TLM service uses SPATEM to disseminate the status of the traffic light controller, traffic lights and intersection traffic information. It transmits continuously in real-time the information relevant for all maneuvers in the of an intersection. The goal is to address all traffic participants using the intersection for travel or cross walking.

2.2.5. IVIMs (Infrastructure to Vehicle Information Messages)

The IVI service is one instantiation of the infrastructure services to manage the generation, transmission and reception of the IVIM messages. An IVIM supports mandatory and advisory road signage such as contextual speeds and road works warnings. IVIM either provides information of physical road signs such as static or variable road signs, virtual signs or road works.

Its content can be updated by the application and it might be transmitted periodically if wished.

2.2.6. SRMs (Signal Request Messages) and SSMs (Signal request Status Messages)

The TLC (Traffic Light Control) service is one instantiation of the infrastructure services to manage the generation, transmission of SRM messages and SSM messages. The TLC service supports prioritization of public transport and public safety vehicles (ambulance, fire brigade, etc.) to traverse a signalized road infrastructure (e.g. intersection) as fast as possible or using a higher priority than ordinary traffic participants.

The SRM is transmitted based on the needs of the vehicle operator and triggered by applications. It might be repeated.

The application generates a SSM to inform the requestor and adjacent traffic participants (e.g. vehicles, pedestrians) about the status of a request. The SSEM is transmitted response to a SRM. Based on changes or incoming SRM with higher priority requests (e.g. public safety "overrules" a Bus request) a revised SSM will be transmitted to reflect the new status.

2.3. IEEE802.11p

IEEE 802.11p is an amendment to the IEEE 802.11 Wi-Fi specification for PHY/MAC (Physical and Medium Access Control) layer communications. Submitted to IEEE for addition to the standard in 2010 by IEEE 802.11 Task Group p, the 11p amendment made several changes to the IEEE 802.11 standard to accommodate inter-vehicular communications. Specifically, these amendments defined the functions that are controlled by the 802.11 MAC and the functions and services that are required to operate in a dynamic environment without having to join a traditional BSS (Basic Service Set, a set of intercommunicating Wi-Fi nodes).

The spectrum utilized is defined by regional bodies, instead of the 802.11 standard. For example, Europe's ITS-G5 reserves 70 MHz (5855 MHz - 5925 MHz) for general V2X communications, of which 30 MHz (5875 MHz - 5905 MHz) is dedicated to traffic safety applications.

IEEE 802.11p is further supplemented by the IEEE 1609 family of standards, collectively referred to as WAVE. The 1609 standards define interfaces and features of the V2X communication stack above the PHY and MAC layers defined by 802.11, including standards describing overall architecture and how to manage security, routing, multichannel operation, communications… ISO also defines its own set of standards. Vehicles use IEEE 802.11p-based technology to form a VANET (Vehicle Ad-hoc Network), which rapidly changes as vehicles come together and move apart. Vehicles regularly broadcast messages, passing that information additionally to road-side stations and other more vulnerable road users.

The IEEE 802.11p standard makes allowances for collision avoidance based on Tiered Contention Multiple Access (TCMA), which is an extension of Carrier Sense Multiple Access with Collision Avoidance (CSMA/CA) which gives higher priority messages a smaller back-off time in the event that a channel is determined busy. Basically, participating network nodes listen for activity on a channel between transmissions, as defined by an inter-frame space parameter. Upon the detection of traffic on a particular channel, nodes pause for a random length back-off period, with a duration between predefined minimum and maximum back-off times. In the case of higher priority traffic, these back-off times are shorter, privileging the transmission of high priority traffic.

In order to allow vehicles with only one radio to take advantage of both safety and service-related communications, the WAVE standard allows for multi-channel operations. Channel switching allows a vehicle with a single radio to divide transmissions between the control channel (CCH), used for safety-related messages, and the service channel (SCH). These divisions are enforced over a repeating interval of 100ms.

Network composition is highly dynamic within VANETs: nodes are added to and removed from the network as quickly as member vehicles enter and leave relative proximity. This lends VANETs a topological instability, with implications for network functions like routing and addressing.

In order to allow authentication between vehicles, the standard describes a private key infrastructure (Vehicular PKI, VPKI), which would require vehicles to carry a set of temporary pseudonymous certificates, which can be used to digitally sign V2X communications, assuring other vehicles of the authenticity of the transmitting vehicle and the validity of transmitted data.

2.3.1. Future

The first version of IEEE 802.11p has been extensively tested and is now safe and reliable. The standard is being improved, as a new version "802.11px" is in development. Improvements might include Low Density Parity Check (LDPC) for channel coding or MIMO.

IEEE 802.11p has had a limited adoption. Some automotive OEMs (Other Equipment Manufacturers) announced plans to adopt this technology in vehicles:

- General Motors: in 2017, GM equipped one of its models (Cadillac CTS) with V2X services and conducted demonstrations.
- Volkswagen: it plans to equip some models from 2019 with IEEE 802.11p capabilities.

2.4. LTE

Sometimes referred to as 3.9G, LTE is the culmination of cooperative standardization efforts conducted by partner organizations across the telecommunications industry, under the auspices of the 3rd Generation Partnership Project (3GPP). Initiated in 2004, the standardization process for the initial LTE architecture was frozen in 3GPP Release 8, in 2008. Deployment of LTE began near the end of 2009, and adoption of the technology quickly spread throughout the telecommunications world, with global implementation continuing today.

LTE brought with it a number of important benefits, not the least of which was finally uniting carriers which had previously made use of different, incompatible 3G standards (namely, UMTS, largely used in Japan, Europe, and China, and CDMA2000, used by carriers in North America and South Korea). Though spectrum allocations for LTE differ by region, and LTE-TDD (LTE-Time Division Duplexing) and LTE-FDD (LTE-Frequency Division Duplexing) employ different transmission schemes, it is economically feasible to produce User Equipment (UE) which can operate in multiple frequencies, using either LTE-FDD or LTE-TDD. This means that phones can be manufactured for use in the global market, and has significantly positive implications for global roaming capabilities. LTE draws its improved performance from a number of enabling technologies, including an IP-based architecture comprising relatively few core network nodes (called the Evolved Packet Core, or EPC) and innovations in the radio access network. Thanks to these technologies, LTE allows for both higher overall data throughput and significantly lower latency than its predecessors.

Based on the 4G requirements defined by the International Telecommunication Union Radio Communications Sector (ITU-R) in the International Mobile Telecommunications Advanced (IMT-Advanced) specification, however, LTE did not meet the requirements of a true 4G network. Satisfying these requirements meant increasing throughput, efficiency, and reliability when compared to LTE networks. In order to meet these increased requirements, the LTE-A, or LTE-Advanced, standard supports new communications technologies, like carrier aggregation, Multiple Input, Multiple Output (MIMO) based spatial multiplexing, and the use of small, low power relay nodes to service cell edges and improve overall coverage.

Unlike 802.11p, which handles scheduling and congestion control at each device, LTE employs a centralized model, where an infrastructural base station (an evolved Node B, or eNB), coordinates the allocation of radio resource blocks. In order to initiate a connection, LTE UEs utilize the Random Access Channel (RACH), a special channel shared by UEs and used specifically to request the allocation of radio resources. At a system level, UEs communicate with the EPC in order to request service, like the establishment of a connection with an external server. In the case of establishing a data connection, the EPC, while also handling book-keeping for tasks like user mobility and user authentication, establishes a dedicated bearer, which can be thought of as a dedicated stream of IP-based traffic, between the UE and a gateway to an external network. This bearer is maintained by the EPC for the duration of the connection, then released when the connection is complete.

Its architecture is briefly explained and represented in Appendix 3.

While the LTE network was designed for use largely with conventional mobile devices, development of the capabilities of the mobile network continues, both for the specific purposes of V2X and more generally. Standards-compliant cellular networks supporting

V2V applications are required to offer end-to-end latency below 100ms, with some support for V2X communications being included in 3GPP release 14 [1], and further support forthcoming in release 15.

The major focus of these new standards is supporting V2V communication via sidelink device to device communication. Sidelink device to device Proximity Services (ProSe) involve the transmission of data directly from device to device, not unlike the peer-to-peer communication which occurs under the DSRC paradigm. The advantages of this technology, as opposed to traditional ad-hoc or cellular signaling, are improved spectrum utilization, energy consumption, and network throughput, as well as lower best-case latency. Unlike DSRC, ProSe-enabled UEs can establish a direct connection either through a direct negotiation of transport resources between devices or in a way intermediated by infrastructural nodes. This allows for the flexible leverage of the spectrum efficiency made possible by centralized coordination and of the reliability of ad-hoc, direct communication when infrastructural connectivity is not available.

2.4.1. Modes of communication

LTE-Advanced supports two V2X communication modes. On the one hand, the infrastructure-based communication mode, also known as Uu-based V2X given that the Uu is the radio interface between UEs and BSs. On the other hand, direct communications, also known as PC5-based V2X due to the use of the PC5 sidelink interface between UEs. Operating scenarios of these two modes are represented in Appendix 2.

2.4.1.1. Mobile network communication (Uu)

LTE-based (and future 5G NR-based) communications via mobile infrastructure. It can be used for V2N communications between a vehicle and an application server. It can also be used to coordinate V2V direct communications via resources allocation managed by a mobile network. The Uu interface supports unicast and multicast connections.

Unicast connections consist in the use of the Uu interface to exchange data between one UE and one eNB, both in uplink and downlink. In this type of connections, scheduling is done in eNB being the resource allocation dynamic or semi-persistent. With dynamic scheduling, the format of the transmissions can be adapted to the channel quality in a fast pace. In unicast, the receivers may provide a feedback to indicate if the receptions are correctly decoded or not, enabling repeat-and-request mechanisms that increase the reliability of the communication. Unicast mode can be useful to send information in point-to-point mode or in point-to-multipoint when the group of receivers is small.

Downlink multicast transmission is covered in LTE-Advanced by Multimedia Broadcast Multicast Service (MBMS). This technology allows the transmission of some data to all the service area of one cell or multiple cells, i.e., it allows single-cell transmission and multi-cell transmission. In MBMS Single Frequency Networks (MBSFN), multi-cell transmission is based on the synchronous transmission of data from multiple cells. A specific set of resources in time (a pattern of subframes) has to be reserved for MBSFN in the physical layer, and each multicast/broadcast service is allocated with a periodic pattern of subframes which is a subset of the whole amount of resources reserved. One advantage of this type of connection is that the synchronous transmission from multiple cells can be combined at the receivers, increasing the probability of correct decoding of the receptions. The main problem of this connectivity option is the strict scheduling of services that cannot be changed in a fast pace producing the addition of scheduling delays to the end-to-end delay. Furthermore, the format of the transmissions cannot be changed dynamically. Both characteristics, make MBSFN inefficient to support traffic with varying patterns (in terms of the size of packets and time between packets).

In Single-Cell Point-To-Multipoint (SC-PTM), transmission of MBMS is conducted in the coverage of a single cell, using the shared downlink channel and with the scheduling done by the eNB. The ability to perform a dynamic scheduling with link adaptation makes SC-PTM suitable to broadcast data with varying traffic pattern, and avoids the scheduling delays of MBSFN. One general drawback of the multicast transmission is the impossibility to signal a bad decoding from the receivers due to the absence of a feedback channel.

2.4.1.2. Direct Communication (PC5)

LTE-based (and future 5G NR-based) communications via a PC5 interface without the support of a wide-area mobile network. This mode shall support V2V, V2I and V2P communications, with no need of a subscription to an operator's data plan. 3GPP Release 14 defines a specific deployment configuration (Mode 3) in which scheduling and interference management of V2V traffic is assisted by an eNB, via control signaling over the traditional cellular network interface. In an alternative configuration (Mode 4), scheduling and interference management of V2V traffic is based on distributed algorithms between the vehicles. Both configurations use GNSS for location and time synchronization, and for CAM and DENM capabilities.

Vehicles and road infrastructure can use both modes simultaneously, as well as use different frequency bands and so do not compete for bandwidth. I consider a special case of the sidelink transmission of LTE-Advanced which is the V2X transmission, specified in Release 14, and hence I use the term Vehicular UE (VUE). Some differences between V2X and the non-V2X sidelink are the increased number of demodulation signals to cope with higher Doppler spreads, the simultaneous transmission in the same subframe of V2X transmission control and data, or the frequency-based resource allocation using special subchannels. One of the main benefits of sidelink communication is its small latency due to the fact that the communication path between two entities communicating does not traverse the radio access and/or the core network. Some drawbacks are the absence of a feedback channel from the receiver to the transmitter, what precludes the implementation of any link adaptation, automatic repeat-and-request method, or even certain MIMO techniques.

2.5. LTE-V Sidelink

LTE sidelink (or device-to-device communication) was introduced for the first time under Release 12 for public safety, and includes two modes of operation: mode 1 and mode 2. Both modes were designed with the objective of prolonging the battery lifetime of mobile devices at the cost of increasing the latency. Connected vehicles require highly reliable and low-latency V2X communications; therefore, modes 1 and 2 are not suitable for vehicular applications.

Release 14 introduces two new communication modes (modes 3 and 4) specifically designed for V2V communications. In mode 3, the cellular network selects and manages the radio resources used by vehicles for their direct V2V communications. In mode 4, vehicles autonomously select the radio resources for their direct V2V communications. In contrast, mode 4 can operate without cellular coverage, and is therefore considered the baseline V2V mode since safety applications cannot depend on the availability of cellular coverage. Mode 4 includes a distributed scheduling scheme for vehicles to select their radio resources and includes the support for distributed congestion control.

2.5.1. Physical layer

It uses single-carrier frequency division multiple access and supports 10 and 20 MHz channels, each one divided into subframes, RBs (Resource Blocks) and subchannels. Subframes are 1ms long (like the TTI [Transmission Time Interval]). An RB is the smallest unit of frequency resources that can be allocated to a user. It is 180 kHz wide in frequency (12 subcarriers of 15 kHz). LTE-V defines subchannels as a group of RBs in the same subframe, and the number of RBs per subchannel can vary. Subchannels are used to transmit data and control information.

The data is transmitted in transport blocks (TBs) over physical sidelink shared channels (PSSCH), and the sidelink control information (SCI) messages are transmitted over physical sidelink control channels (PSCCH). A TB contains a full packet to be transmitted, e.g., a beacon or cooperative awareness message. A node that wants to transmit a TB must also transmit its associated SCI, which is also referred to as a scheduling assignment. The SCI includes information such as the modulation and coding scheme (MCS) used to transmit the TB, the RBs it uses, and the resource reservation interval for semipersistent scheduling (SPS). This information is critical for other nodes to be able to receive and decode the transmitted TB, so the SCI must be correctly received. A TB and its associated SCI must always be transmitted in the same subframe. I refer to the transmission of an SCI and its associated TB in the same subframe as SCI + TB (or hybrid automatic repeat request transmission in the 3GPP).

LTE-V defines two subchannelization schemes:

- Adjacent PSCCH + PSSCH: The SCI and TB are transmitted in adjacent RBs. For each SCI + TB transmission, the SCI occupies the first two RBs of the first subchannel utilized for the transmission. The TB is transmitted in the RBs following the SCI, and can occupy several subchannels (depending on its size). If it does so, it will also occupy the first two RBs of the following subchannels.
- Nonadjacent PSCCH + PSSCH: The RBs are divided into pools. One pool is dedicated to transmit only SCIs, and the SCIs occupy two RBs. The second pool is reserved to transmit only TBs and is divided into subchannels.

TBs can be transmitted using quadrature phase shift keying (QPSK) or 16 quadrature amplitude modulation (QAM), whereas the SCIs are always transmitted using QPSK. LTE-V uses turbo coding and normal cyclic prefix. LTE-V subcarriers have a total of 14 symbols per subframe, and four of these symbols are dedicated to the transmission of demodulation reference signals (DMRSs) to combat the Doppler effect at high speeds. DMRSs are transmitted in the third, sixth, ninth, and 12th symbol of each subcarrier per subframe. The maximum transmit power is 23 dBm, and the standard specifies a sensitivity-power-level requirement at the receiver of –90.4 dBm and a maximum input level of –22 dBm.

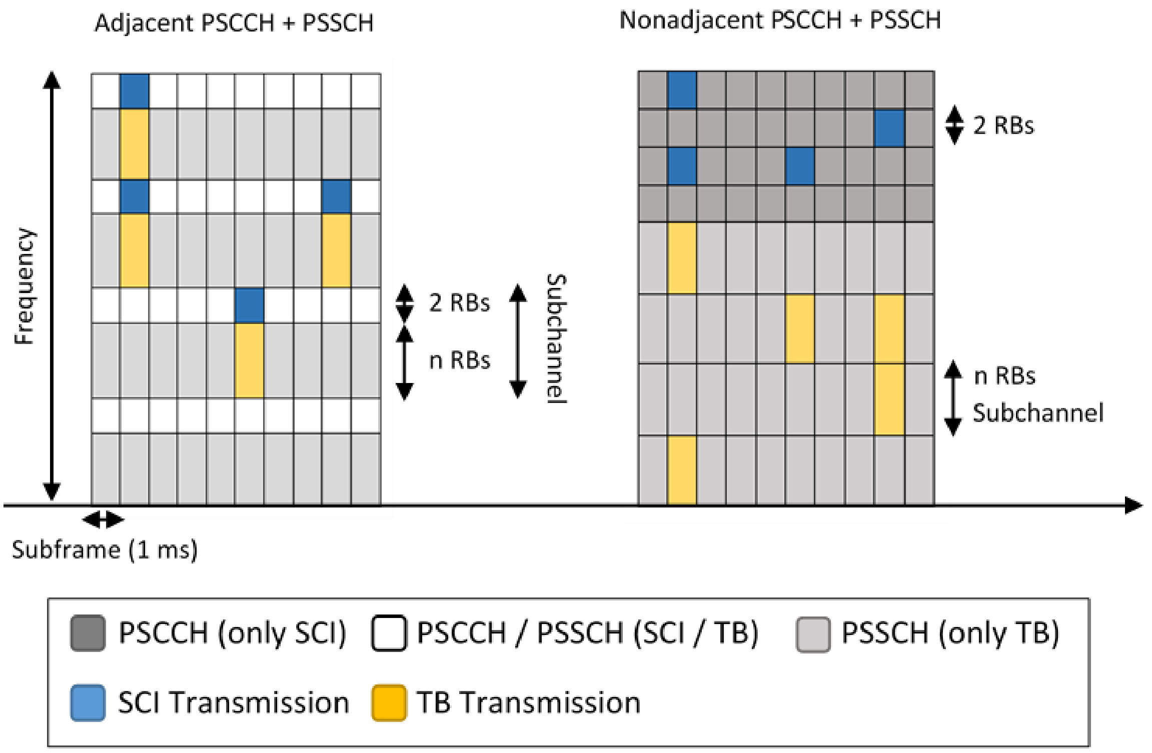

Figure 2. LTE-V subchannelization [25]

2.5.2. Mode 4

Vehicles communicate under mode 4 selecting their radio resources independently of whether they are under cellular coverage or not.

Under cellular coverage, the network decides the V2X channel configuration and informs the vehicles, with a message including the carrier frequency, the resource pool, synchronization references, the subchannelization scheme, the number of subchannels per subframe, the number of RBs per subchannel…

Without cellular coverage, the vehicles use a set of preconfigured parameters. The V2X resource pool indicates which subframes of a channel are used, so the rest can be utilized by other services. The standard includes the option of zoning.

In mode 4 vehicles select their subchannels with a sensing-based SPS scheme. Mode 4 also supports congestion control.

2.5.3. Mode 3

The selection of subchannels is managed by the eNB. Therefore, it is only available under cellular coverage. Each operator can implement its own resource management algorithm, classified among this two categories:

- Dynamic scheduling: vehicles request subchannels to the eNB for every transmission. Increases overhead.
- SPS: the eNB reserves subchannels and decides for how long the reservation is maintained.

Vehicles operating under mode 3 can be supported by different cellular operators or by public land mobile networks (PLMNs). To enable direct communications, an inter-PLMN (Public Land Mobile Network) architecture has been defined for two scenarios:

- Vehicles supported by different PLMNs share the same carrier or transmit in different carriers. In this case, vehicles must be able to simultaneously receive in multiple carriers the transmissions of vehicles supported by other PLMNs. To this aim, each PLMN broadcasts in the sidelink V2X configurable parameters the necessary information so that the vehicles it supports can receive the packets transmitted by vehicles supported by other PLMNs.
- Vehicles supported by different PLMNs share the same carrier, but each PLMN is assigned part of the RBs of the carrier. The standard does not specify how the resources should be split among the PLMNs, but introduces a coordination mechanism (through the V2X control function) between PLMNs to avoid packet collisions.

2.5.4. Congestion control

Release 14 supports congestion control in mode 4. The standard does not specify a particular congestion control algorithm but defines the related metrics and possible mechanisms to reduce the channel congestion. Each time a vehicle has to transmit or retransmit a packet, it estimates the channel busy ratio (CBR) and channel occupancy ratio (CR). If the packet is going to be transmitted at subframe *n*, the measurements are done at subframe *n–4*. The CBR provides an indication of the level of channel congestion, and is defined as the amount of subchannels in the previous 100 subframes that experience an average RSSI higher than a preconfigured threshold. The CR quantifies the channel occupancy generated by the transmitting vehicle. It is defined as the amount of subchannels that the transmitting vehicle utilizes during a period of 1,000 subframes.

When a vehicle has to transmit a packet (or its redundant version), it measures the CBR and quantifies its CR. If its CR is higher than its limit value, there are several mechanisms defined to reduce it:

- Packet dropping
- Reducing the number of transmission per packet
- Augmenting the MCS
- Reducing the reserved subchannels
- Decreasing the transmission power

Mode 3 does not implement a distributed congestion control process as defined in mode 4. In mode 3, the eNB manages the subchannels and decides how to reduce the channel occupancy. Such decisions can take into account the CBR levels locally measured by vehicles. To this aim, the eNB can request each vehicle periodically (the eNB determines the period) or, on demand, report its measured CBR.

2.6. Use cases

The following tables present the use cases for V2X communications as they are defined by 3GPP in their corresponding releases ([1] and [5]). The first one contains the Release 14 use cases for LTE-V2X and the second one contains its enhanced version, still in development with Release 15.

2.6.1. LTE

Mainly focused on safety applications.

LTE-V2X USE CASES		
1. Forward Collision Warning **2.** Control Loss Warning **3.** V2V emergency vehicle warning **4.** V2V emergency stop **5.** Cooperative Adaptive Cruise Control **6.** V2I emergency stop **7.** Queue warning **8.** Road safety services **9.** Automated Parking System **10.** Wrong way driving warning **11.** V2X message transfer under MNO control **12.** Pre-crash Sensing Warning	**13.** V2X in areas outside network coverage **14.** V2X road safety service via infrastructure **15.** V2N Traffic Flow Optimization **16.** Curve Speed Warning **17.** Warning to Pedestrian against Pedestrian Collision **18.** Vulnerable Road User (VRU) Safety **19.** V2X by UE-type RSU **20.** V2X Minimum QoS **21.** V2X access when roaming	**22.** Pedestrian Road Safety via V2P awareness messages **23.** Mixed Use Traffic Management **24.** Enhancing Positional Precision for traffic participants **25.** Privacy in the V2V communication environment **26.** V2N to provide overview to road traffic participants and interested parties **27.** Remote diagnosis and just in time repair notification

Table 1. LTE-V2X Use cases

2.6.2. 5G

Keeps taking into account safety-related use cases but adds platooning and automated driving applications, mainly due to an improvement in some critical features (consistent ultra-fast data speeds, ultra-low latency…).

5G-V2X USE CASES		
1. eV2X support for vehicle platooning **2.** Information exchange within platoon **3.** Automotive: sensor and state map sharing **4.** eV2X support for remote driving **5.** Automated cooperative driving for short distance grouping **6.** Collective perception of environment **7.** Communication between vehicles of different 3GPP RATs **8.** Multi-PLMN environment	**9.** Cooperative collision avoidance (CoCA) of connected automated vehicles **10.** Information sharing for partial/conditional automated driving **11.** Information sharing for high/full automated driving **12.** Information sharing for partial/conditional automated platooning **13.** Information sharing for high/full automated platooning **14.** Dynamic ride sharing **15.** Use case on multi-RAT **16.** Video data sharing for assisted and improved automated driving (VaD)	**17.** Changing driving-mode **18.** Tethering via Vehicle **19.** Use case out of 5G coverage **20.** Emergency trajectory alignment **21.** Teleoperated support (TeSo) **22.** Intersection safety information provisioning for urban driving **23.** Cooperative lane change (CLC) of automated vehicles **24.** Proposal for secure software update for electronic control unit **25.** 3D video composition for V2X scenario

Table 2. 5G-V2X Use cases

3. Methodology and project development

3.1. System modelling

3.1.1. Real model

V2X applications occur in complex situations and environments which can be difficult to simulate. Many variables might be needed to properly define a scenario where to analyze the performance of this technology.

1. *Road traffic:* mobility models are used to define the behavior of the traffic in a certain area. Each vehicle might have its traffic pattern. The speed is not constant, and for example in urban scenarios, cars might stop and go in intersections. Vehicle densities, then, might also be variable. Some realistic models are available, such as the Krauss car following model.

2. *Propagation:* various parameters should be defined, like whether is a Line-of-sight (LoS) or a NLoS scenario. Links' properties between BSs and VUEs should also be specified: typically, a 2 GHz model for the link between BSs and VUEs, and a 5.9 GHz one for the link between VUEs. Each link would be defined by a pathloss model (for example, WINNER+ B1). The shadowing might also be modeled, typically with a log-normal distribution.

3. *Network deployment:* several parameters regarding the antennas and cables used should be taken into account for both the BS and the VUE: bandwidth, transmission power, number of antennas, its gain, downtilt, height, pattern, beamwidth and front-back ratio, and the cable loss. A noise figure might also be defined.

4. *Messages:* each message type has its own parameters: size, size distribution, periodicity, delay and modulation and coding scheme (MCS).

3.1.2. Simplification

With the aim of avoiding complex simulations relying on different licensed software solutions, the model has been heavily simplified.

1. *Road traffic:* constant speeds and vehicle densities are assumed. The road topology definition is basically limited to a number of lanes and their directions. Car arrivals modeled as *Poisson* arrivals.

2. *Propagation:* 5.9 GHz link used, but none of the parameters regarding the propagation has been taken into account.

3. *Network deployment:* parameters of the antennas also omitted. No loss is assumed and neither is noise.

4. *Messages:* defined by all the parameters mentioned except form the MCS, which is not taken into account. Distributions assumed to be exponential or deterministic.

These simplifications on the definition of the model allows it to be much lighter than it would. A critical issue not taken into account is the Random Access in LTE (RACH), which will be not considered in the model.To be analyzed with queuing theory the system is modeled as one server with infinite queue length and 3 different traffic sources, one category each one. Inter-arrival times assumed to be exponential.

Given these assumptions, the model ends up being a M/G/1 queue and the calculation of its parameters is summarized in the next section.

3.2. Queuing theory

This methodology was adopted in ITU-R recommendation [6] to calculate spectrum requirements of IMT (International Mobile Telecommunications).

The required system capacity is calculated for the services using mean delay requirements. Both periodical traffic (BSM or CAM) and event-triggered traffic are taken into account. The model used is an M/G/1 with non-preemptive priorities (M/G/1 NPP), which means that, when a job with a higher priority than the current one arrives, the service of the current job is not interrupted. Separate queues are used for different priorities, and each one uses the FCFS (First Come, First Served) scheduling discipline.

The priority ranking is p = 1, 2, …, P, where p = 1 is the highest priority and p = P the lowest.

The calculation of the vehicle density is needed to compute the lambda for the V2X scenario. It can be found with the following expression:

$$density = \frac{Vehicle_{range} \cdot 2 \cdot lanes}{speed \cdot TTC + Vehicle_{length}} \tag{1}$$

- TTC: time-to-collision
- Vehicle length: in average, 4.7 meters

As the time-to-collision parameter might be very variable, a simplification of the formula is made with another parameter, the inter-vehicle gap:

$$density = \frac{Vehicle_{range} \cdot 2 \cdot lanes}{inter\_vehicle\_gap + Vehicle_{length}} \tag{2}$$

The mean service time is calculated as follows:

$$T_{sp} = \frac{L_p}{C} \tag{3}$$

Its second moment, if deterministic:

$$T_{sp}{}^{(2)} = T_{sp}{}^{2} \tag{4}$$

If exponential:

$$T_{sp}{}^{(2)} = 2T_{sp}{}^{2} \tag{5}$$

And if uniform between two values (*a* and *b*):

$$T_{sn}{}^{(2)} = \frac{a^2 + a \cdot b + b^2}{3 \cdot C^2} \tag{6}$$

The packet arrival rate is obtained as:

$$\lambda_p = \frac{T_{sp}}{L_p} \tag{7}$$

And, taking into account the density:

$$\lambda_{V2Xp} = \lambda_p \cdot density \tag{8}$$

A ρ parameter results from:

$$\rho_p = \lambda_p \cdot T_{sp} \tag{9}$$

A residual time is also calculated:

$$T_{RES} = \sum_{i=1}^{P} \frac{\lambda_i {T_{si}}^{(2)}}{2} \tag{10}$$

The mean waiting time is obtained as:

$$T_{wp} = \frac{T_{RES}}{(1 - \sum_{i=p}^{P} \rho_i)(1 - \sum_{i=p+1}^{P} \rho_i)} \tag{11}$$

So, for the most cases:

$$T_{w1} = \frac{T_{RES}}{1 - \rho_1} \tag{12}$$

$$T_{w2} = \frac{T_{RES}}{(1 - \rho_1)(1 - \rho_1 - \rho_2)} \tag{13}$$

$$T_{w3} = \frac{T_{RES}}{(1 - \rho_1 - \rho_2)(1 - \rho_1 - \rho_2 - \rho_3)} \tag{14}$$

And, finally, the mean packet delay D_p results from the sum of the mean waiting time and the mean service time:

$$D_p = T_{wp} + T_{sp} \tag{15}$$

To obtain the total results, the proportion of each category must be computed:

$$\lambda_T = \sum \lambda_p \tag{16}$$

$$proportion_p = \frac{\lambda_p}{\lambda_T} \tag{17}$$

And then,

$$T_s = \sum proportion_p \cdot T_{sp} \tag{18}$$

$$T_w = \sum proportion_p \cdot T_{wp} \tag{19}$$

And finally,

$$D = T_w + T_s \tag{20}$$

3.3. Scenarios

For the next scenarios, the length considered for each car will be of 4.7 meters and the mean range of 320 meters. The parameters, based on requirements defined by 3GPP [4] and ETSI [18], regarding the messages used are the following:

- **CAMs** (second priority), periodic
  - Size: 300 Bytes
  - Periodicity: 100 ms
- **DENMs** (first priority), event-triggered
  - Size: 300 Bytes
  - Periodicity: depending on the scenario
    1. 1 s
    2. 0.5 s
    3. 2 s
- **SPaTs** (third priority), traffic lights and intersection traffic
  - Size: 400 Bytes
  - Periodicity: 100 ms
- **MAPs** (third priority), road topology
  - Size: variable, depending on the scenario
    1. 800 Bytes
    2. 1200 Bytes
    3. 400 Bytes
  - Periodicity: 1 s

3.3.1. Large city entrance

a. Number of lanes: 8, same direction

b. Speed: 60 km/h

c. Inter-vehicle gap: 3 m

d. Vehicle density: 333 vehicles/range

e. Messages needed:

   i. DENMs

   ii. CAMs

   iii. MAPs

3.3.2. Complex intersection

a. Number of lanes: 8, four different directions

b. Speed: 30 km/h

c. Inter-vehicle gap: 1 m

d. Vehicle density: 450 vehicles/range

e. Messages needed:

   i. DENMs

   ii. CAMs

   iii. MAPs

   iv. SPaTs

3.3.3. Freeway

a. Number of lanes: 6, two directions

b. Speed: 120 km/h

c. Inter-vehicle gap: 4 m

d. Vehicle density: 220 vehicles/range

e. Messages needed:

   i. DENMs

   ii. CAMs

   iii. MAPs

3.4. Calculations

A *Matlab* program (see Appendix 1) has been developed in order to execute the following tests. As several tests are needed to extract conclusions on which basic requirements the LTE-V2X should have, some hypothesis on the input parameters must be made.

Summing up the scenarios defined before,

	Scenario 1 *City entrance*	Scenario 2 *Intersection*	Scenario 3 *Freeway*
Lanes	8	8	6
Speed [km/h]	60	30	120
Density [v/range]	333	450	220
Messages	• CAM • DENM • MAP	• CAM • DENM • MAP • SPaT	• CAM • DENM • MAP

Table 3. Scenarios' parameters

As well as the parameters of the messages expected to use in each scenario,

	DENM *Event-triggered*	CAM *Periodic*	MAP *Road topology*	SPaT *Intersections*
Priority	1	2	3	3
Size [Bytes]	300	300	• S1: 800 • S2: 1200 • S3: 400	400
Periodicity	• S1: 1 s • S2: 0.5 s • S3: 2 s	100 ms	1 s	100 ms
Packet rate	• S1: 1 pps • S2: 2 pps • S3: 0.5 pps	10 pps	1 pps	10 pps

Table 4. Messages' parameters

Given that MAP messages describe the road topology [21], they usually are the most heavy-sized. On scenarios such as freeways, where the road and the elements on it are simple, this type of message will be lighter than on other more complex scenarios, where it will need to be larger.

As for the event-triggered messages, in order to simulate its periodicity different values have been defined depending on the scenario. The more complex the scenario is, the smaller the frequency should be, as more events might arise.

Regarding the packet rate values, they are calculated from the defined periodicity.

3.4.1. Density

The density values defined in previous sections have been computed with the formula provided, (2). In addition of using these values for the computing of the delay, a sweeping of a range of densities might be done to find a limit value. To decide which the last value in this range should be, I will assume an inter-vehicle gap of 0.5 meters and 10 lanes (worst case situation).

$$sweeping_{range} = [0, 616]\ m$$

3.4.2. Capacity

With the aim of finding a capacity requirement using M/G/1, I need to have one parameter fixed, the mean total delay. Based on the literature consulted ([24], [25], [26], [27]), the standard delay for a V2X scenario should not be more than 50 milliseconds.

$$D_{max} = 50\ ms$$

This value means half the periodicity of the messages with the highest packet rate, which seems suitable for a V2X application.

Moreover, I could define a delay for each category, as they have different priorities and, therefore, the less prioritized packets might have greater delays than the most prioritized ones.

Then,

<table>
<tr><th></th><th>DENM
Event-triggered</th><th>CAM
Periodic</th><th>MAP
Road topology</th><th>SPaT
Intersections</th></tr>
<tr><td>**Priority**</td><td>1</td><td>2</td><td colspan="2">3</td></tr>
<tr><td>**Delay [ms]**</td><td>10</td><td>10</td><td colspan="2">50</td></tr>
</table>

Table 5. Messages' delays

The expected behavior of the results is to increase along with density and eventually saturate.

3.4.3. Delay

One of the objectives of the project was to obtain delay results (total and partial for each category) and, to do so, setting capacity values was needed. From the literature on the issue [24], I extracted a typical value for V2X:

$$C = 15\ Mbps$$

For the delay testing, the value used will be slightly smaller to test in worst cases.

Therefore,

	DENM *Event-triggered*	CAM *Periodic*	MAP *Road topology*	SPaT *Intersections*
Priority	1	2	3	
C [Mbps]	10			

Table 6. Messages' capacities

As capacity, the expected behavior of the results is to increase along with density and eventually saturate.

4. Results

4.1. Capacity requirements

4.1.1. Results

The capacity results computed for each scenario are presented in the table below.

	Scenario 1 *City entrance*			Scenario 2 *Intersection*			Scenario 3 *Freeway*		
Total capacity	10.91 Mbps			31.67 Mbps			6.30 Mbps		
	Cat. 1	Cat. 2	Cat. 3	Cat. 1	Cat. 2	Cat. 3	Cat. 1	Cat. 2	Cat. 3
C/cat. [Mbps]	2.21	9.08	10.94	4.53	13.69	31.68	1.46	5.83	6.32

Table 7. Capacity results

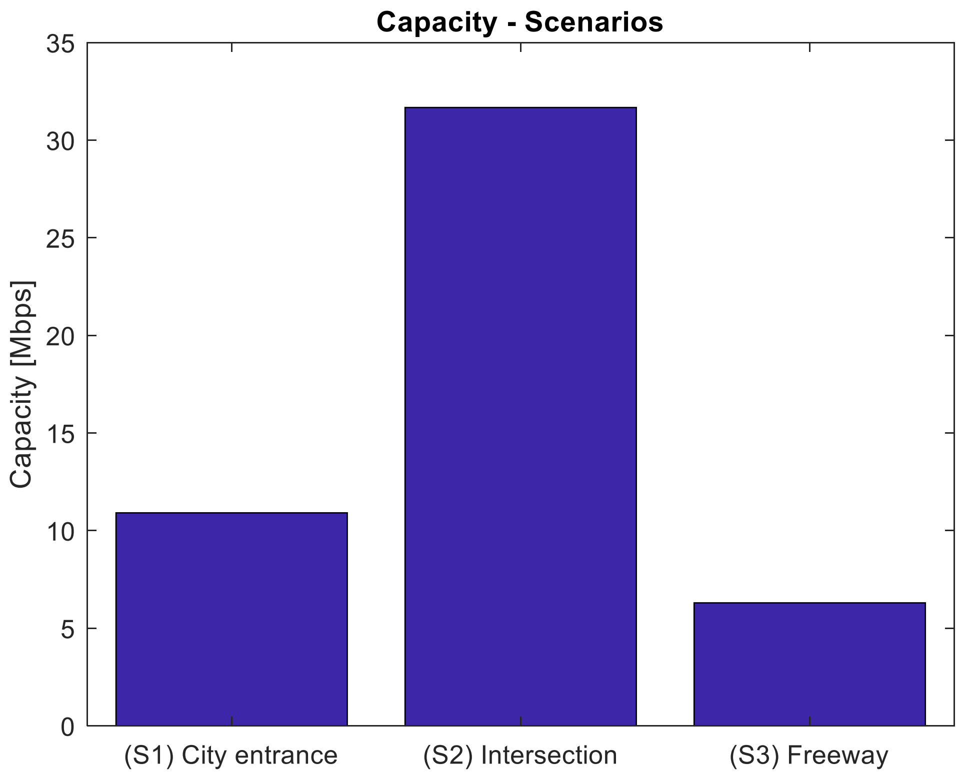

Figure 3. Total capacity - density

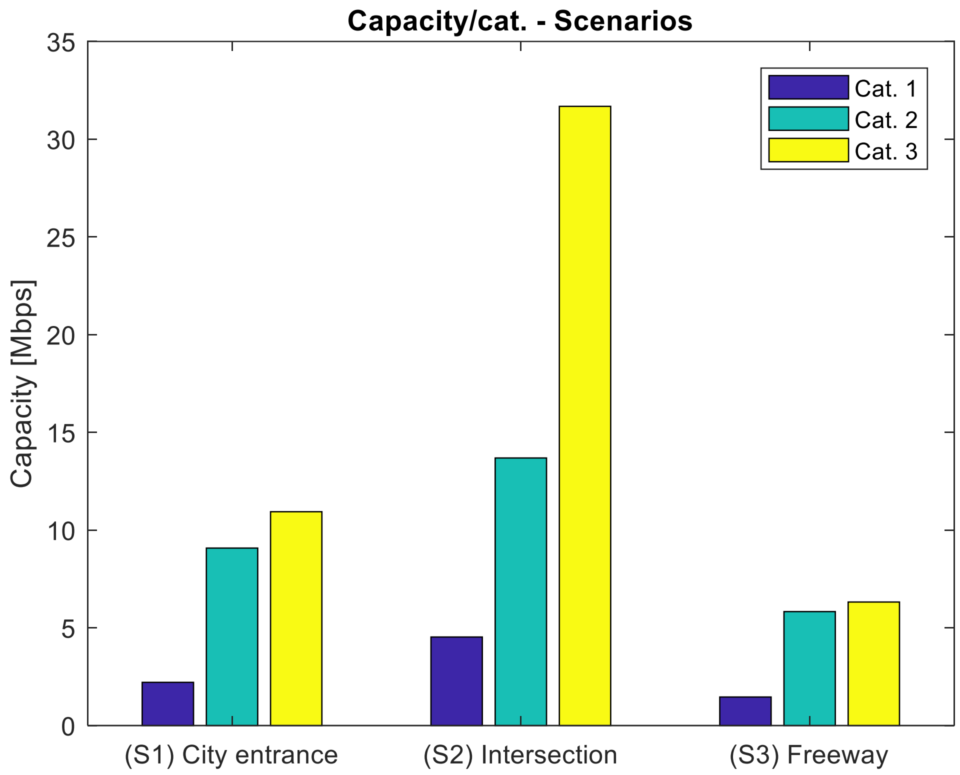

Figure 4. Capacity - density for each category

The same test varying the density for each scenario configuration has also been done, resulting in a linear evolution of the capacity along with the vehicle density.

4.1.2. Conclusions

As expected, the capacity needed to support a complex urban scenario clearly increases compared to the interurban scenarios, mainly due to two reasons. Firstly, the vehicle density is larger, and secondly, 4 packet types are needed in the intersection scenario, as additional information has to be given by the SPaTs, and the MAPs' size must be larger to describe a complex road topology.

From the results obtained, two requirements might be defined, one for an urban scenario and the other for an interurban scenario.

Interurban	Urban
15 Mbps	35 Mbps

Table 8. Capacity requirements

The first capacity requirement should apply in freeways as well as big suburban roads, whilst the second one should be applied inside towns and cities. Note that the second requirement is quite larger than expected. Compared to the typical value defined in 3.4, the one found for the urban situation is clearly higher and not acceptable in LTE-V2X.

4.2. Delay requirements

4.2.1. Results

The delay results are presented below for each scenario.

	Scenario 1 *City entrance*			Scenario 2 *Intersection*			Scenario 3 *Freeway*		
Total delay	Sat.			Sat.			0.57 ms		
	Cat. 1	Cat. 2	Cat. 3	Cat. 1	Cat. 2	Cat. 3	Cat. 1	Cat. 2	Cat. 3
D/cat. [ms]	0.5	2.5	Sat.	1.5	Sat.	Sat.	0.39	0.57	0.71

Table 9. Delay results

Delay results increase along with the scenario requirements, due to the vehicle density and the messages traffic. In both complex scenarios, category 2 and 3 are unstable and saturate.

The same test varying the density for each scenario configuration has also been done. For scenario 1,

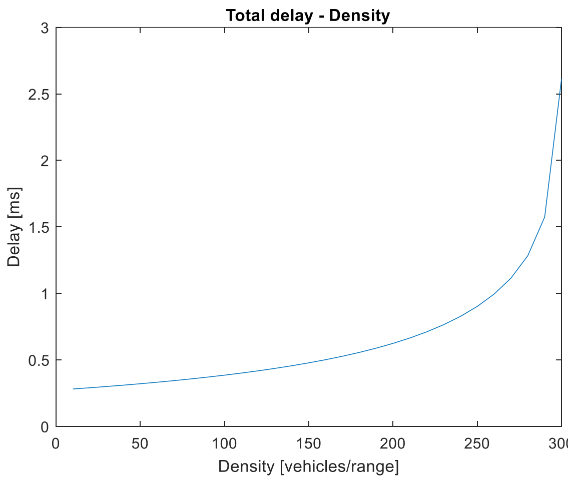

Figure 6. Total delay - density for scenario 1

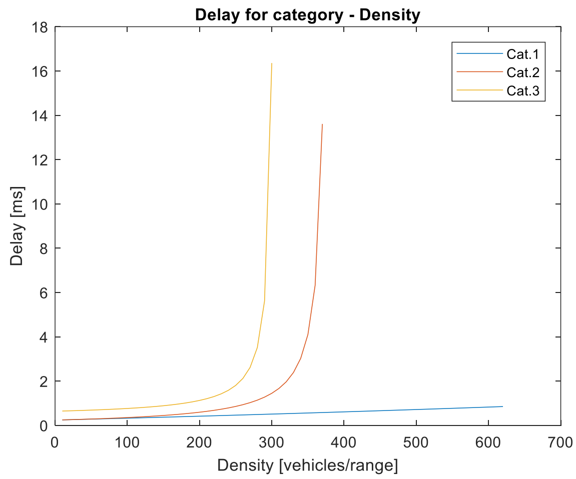

Figure 5. Delay - density for each category, for scenario 1

For scenario 2,

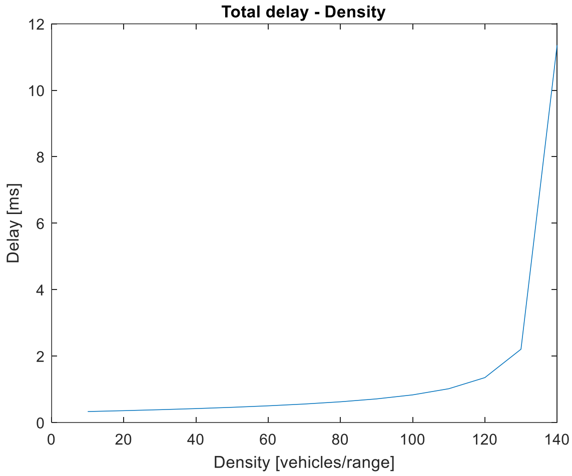

Figure 8. Total delay - density for scenario 2

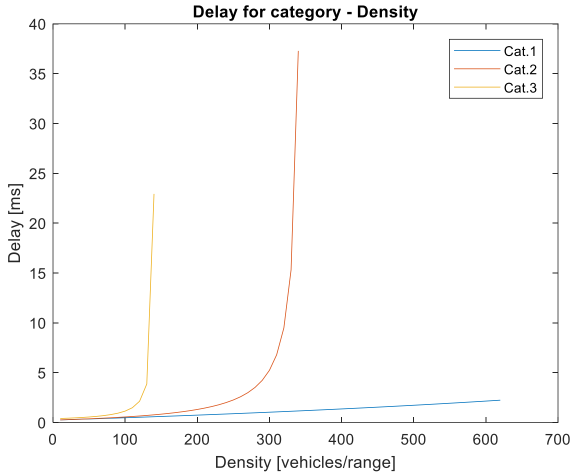

Figure 7. Delay - density for each category, for scenario 2

And for scenario 3,

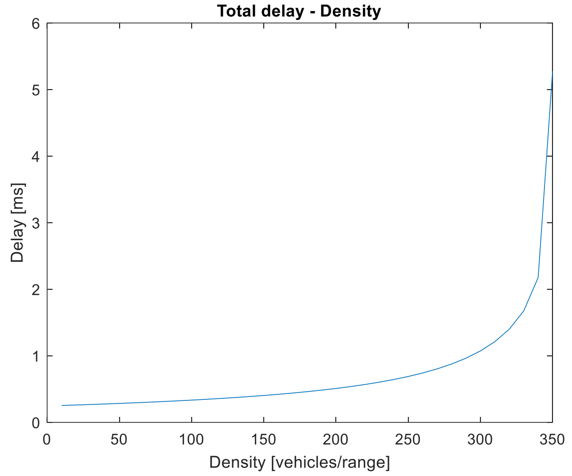

Figure 10. Total delay - density for scenario 3

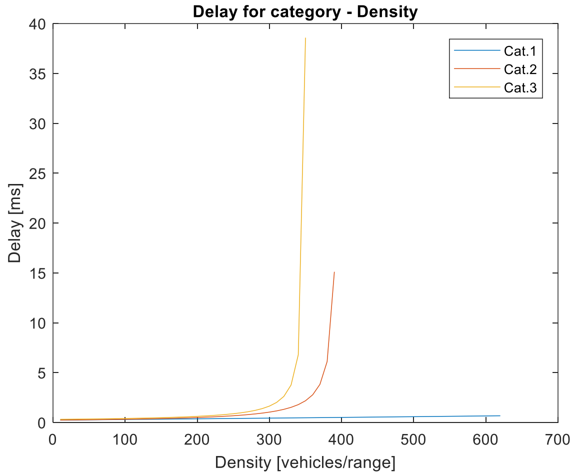

Figure 9. Delay - density for each category, for scenario 3

4.2.2. Conclusions

Firstly, note that the system gets easily saturated when tested in elevated vehicle densities, especially in the second scenario. In this scenario the third category's packet rate is larger than in the rest of the scenarios, as two different packets belong to it (MAPs and SPaTs), having the SPaT a greater periodicity (100 ms).

In the first scenario (City entrance), the system offers stability until 300 vehicles/range of density, with a total delay of 2.61 ms, being the delay of the third category packets (MAPs) of 16.36 ms.

In the most complex scenario (Urban intersection), the system is clearly more unstable, due to the larger packet rates and sizes of the third category (MAPs + SPaTs). It can only perform well below 140 vehicles/range of density, with a total delay of 11.36 ms.

In a freeway scenario, the system keeps stable until reaching a density of 350 vehicles. At this point, despite being the delay for the third category (MAPs) of 38.58 ms, the resulting total delay is 5.27 ms, mainly due to its lesser packet rate.

Regarding the delays obtained in these tests, they all are below the threshold suggested in section 3.5.2, 50 ms. However, having observed the system behaviour in the three proposed scenarios, the results regarding vehicle densities are not so satisfactory. For the simplest scenario, the densities supported are higher than the ones I previously defined (the density suggested for a freeway scenario was 220 vehicles/range), and for the City entrance one, the maximum density supported by the system is quite near the value suggested (~330 vehicles/range). Nevertheless, for the Intersection scenario the vehicle densities reached are far below an acceptable value (the one suggested was 450 vehicles/ranges). The system is clearly unable to support high message traffic (DENMs + CAMs + heavy MAPs + SPaTs) in high density situations.

In order to avoid this issue, more capacity would be needed. Some tests concluded the capacity should be ~45 Mbps to comply both the density and delay requirements in the second scenario.

$$C = 45\ Mbps$$

The results for this capacity value:

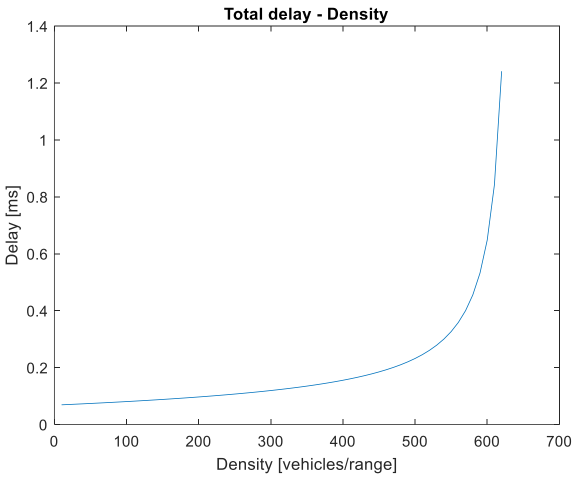

Figure 12. Total density - delay with no saturation

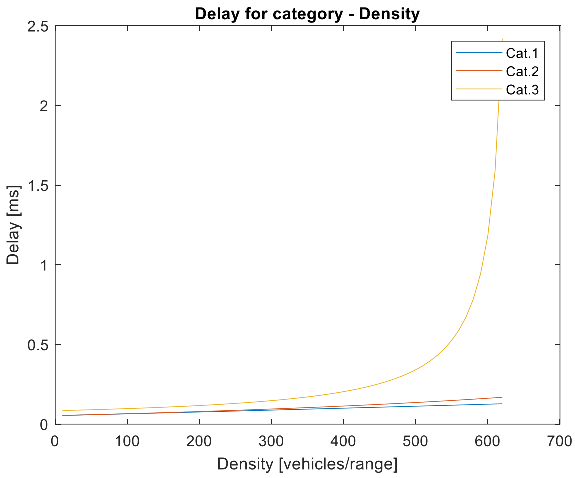

Figure 11. Delay - density for each category, no saturation

Given the observed results, on one hand, to support V2X applications, the maximum delay requirement could be:

$$D_{max} = 40\ ms$$

Which is achieved in all cases, and is low enough to be able to serve safety-related applications.

On the other hand, though, the capacity requirement is higher than the one found in section 4.1 and the one assumed to be typical for V2X (15 Mbps). The needed capacity to handle complex urban situations is not feasible in a LTE-V2X system.

5. Budget

As this project is purely based on software and had an eminently theoretical objective no major costs are involved in its development.
Nevertheless, two costs could be taken into account: the workforce and a software license.

5.1. Workforce

Assuming I am a Junior Engineer or a college intern,

- Salary: assuming the typical salary for an UPC student doing an internship in a company.

$$Salary = 8€/h$$

- Hours invested:

$$Hours_{worked} = 360\ h$$

Resulting in a gross salary of:

$$Salary_{gross} = 2280€$$

Applying a 2% discount due to the condition of intern, the final net salary is:

$$Salary_{net} = 2234.40€$$
$$Salary_{monthly} = 446.88€/month$$

5.2. Software license

Matlab is a multi-paradigm numerical computing environment and proprietary programming language developed by *MathWorks*, which is also proprietary, so users are subject to a vendor lock-in.
Assuming the license used is an educational type one, which is perpetual:

$$license = 500€$$

And given that the typical amortization of a software license is of 33% in 6 years,

$$amortization = \frac{500 - 0.33 \cdot 500}{6} = 55.83€\ in\ a\ year$$

But as the project duration is approximately 5 months:

$$amortization = 23.26€$$

6. Conclusions and future development

Vehicle-to-everything, including vehicle-to-vehicle, to-pedestrian, to-infrastructure and to-network, will improve road safety and traffic efficiency, and will have an important impact on other fields such as autonomous vehicles. Two solutions are being developed (or already arriving at the market) to support V2X applications and comply its requirements, LTE-V2X and IEEE802.11p.

However, the definition of the LTE sidelink technology in the 3GPP Release 14 puts this one ahead of DSRC due to future development reasons, as in Release 15, with the 5G arrival, V2X services will be enhanced. In addition, some economic studies claim that LTE-V2X deployment will have less costs [30].

Anyway, the bibliographic research conducted for this project leads to the conclusion that C-V2X needs to be developed a lot more to fulfil the expectations the market has. The deployment of LTE-V2X will take advantage of the wide penetration LTE has worldwide, but should accelerate to hit the market as soon as possible and start substituting DSRC, which is expected to be introduced sooner.

The results of the calculations on the defined models reinforce the previous statement. LTE-V2X fails to have a decent performance concerning its delay in complex scenarios, where elevated messages traffic and vehicle density are involved. Despite not being taken into account in the calculations, the unavoidable packet collisions [26] entail that, for example, further enhancements to the sensing-based SPS protocol, or alternative schemes, should be investigated.

In the near future, more solutions for V2X communications will be provided by 3GPP with 5G and eV2X (enhanced V2X). The requirements of eV2X shall satisfy stringent reliability, low latency, high data rates and larger communication range even in the high density scenarios. The proper enhancements have to be proposed especially with the 5G-NR sidelink operations.

Bibliography

[1] 3GPP TR 36.885, "Study on LTE-based V2X Services (Release 14)", V14.0.0, June 2016.

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Appendices

Appendix 1: Matlab code

Once defined the hypothesis and scenarios, one of the aims of this project is to simulate various simplified V2X situations and run some tests to extract conclusions regarding the requirements of a few important parameters.

Given that real simulations have an elevated both software and time cost, I decided to develop some *Matlab* scripts which would compute the parameters needed using mainly the Queue theory for V2X.

The program requires some parameters and can run 4 different simulations:

1. Delay calculation for 3 predefined packet rates, which are equal for each category
2. Delay calculation for different packet rates for each category, inputted by the user
3. Delay calculation for different capacities for each category, with the same or with different packet rates for each category
4. Capacity calculation for a delay defined by the user

The simulation can be computed by just one scenario or for all of them. Once it has finished, the results are printed and plotted.

Pseudocode

Although a lot of testing scripts were made, the final working version uses 6 of them. Two scripts contain the Queue theory computation, two are needed to generate the view for the user and two more are used for auxiliary calculations.

The program's main file is the one which handles the view. When executed, the view is generated, and the computation starts when one of the 4 buttons is pressed. This script gets all the input parameters and calls for one of the two functions that compute the M/G/1 calculations. These use other functions to obtain, for example, the vehicle density, and return a total delay, a delay for each category or a capacity, depending on the parameters introduced. The code is iterated for all the scenarios, if selected. Finally, the main program checks if the results are feasible (not negative signed results, for example), prints them in the view and generates several figures depending on the obtained results.

After testing, the mean execution time in a worst case scenario is 0.6811 seconds.

GUI

The view for the program is designed using GUIDE and consists in a simple interface for inputting the parameters and viewing the results.

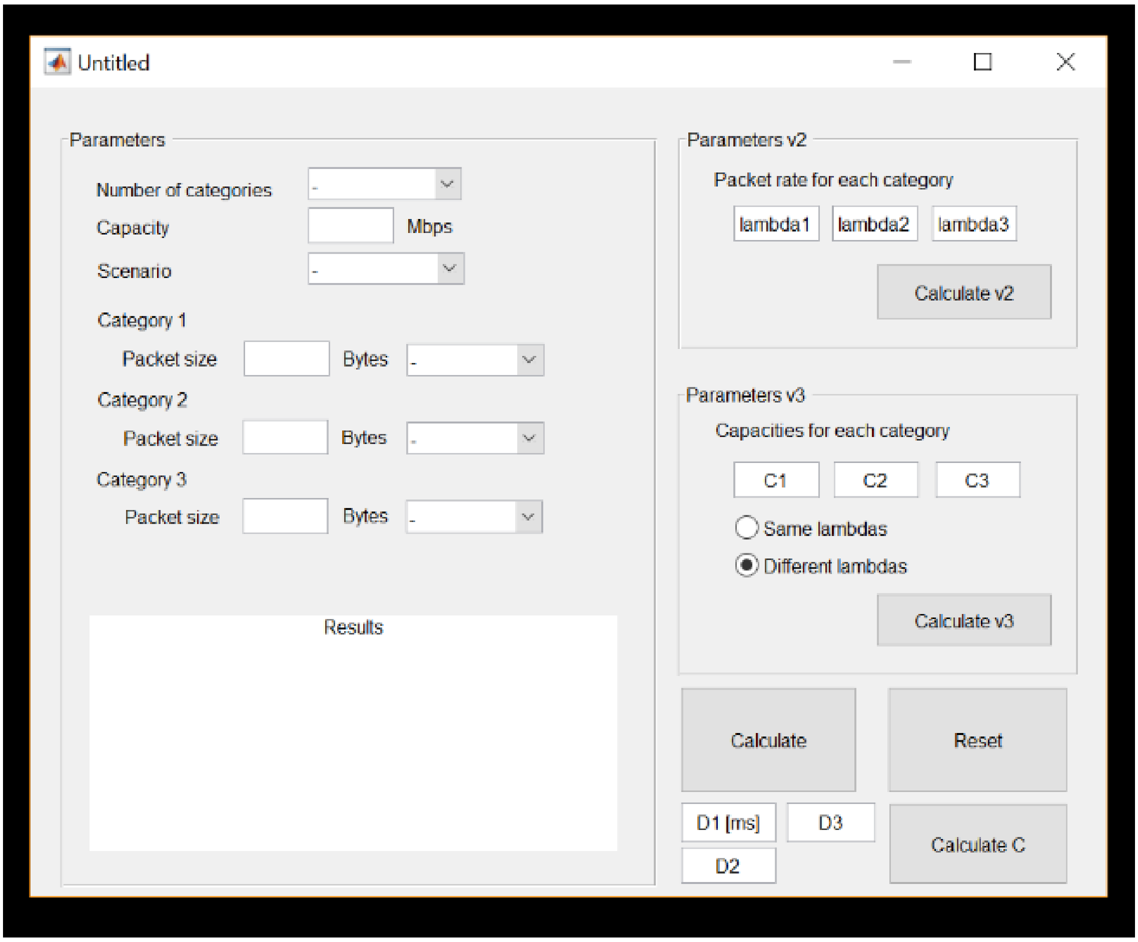

Figure 13. Program view

Appendix 2: LTE-V2X modes' operating scenarios

General scenarios

A number of scenarios of possible V2X services have been identified:

1. V2V operation based on PC5/Uu

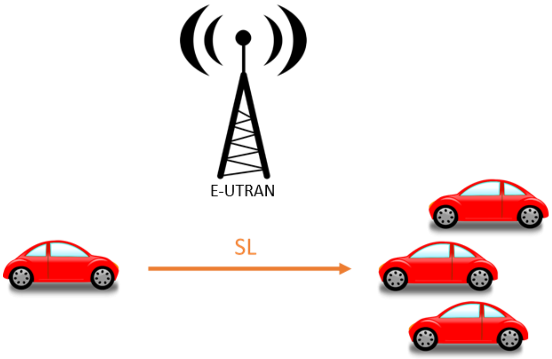

Figure 15. PC5 based V2V

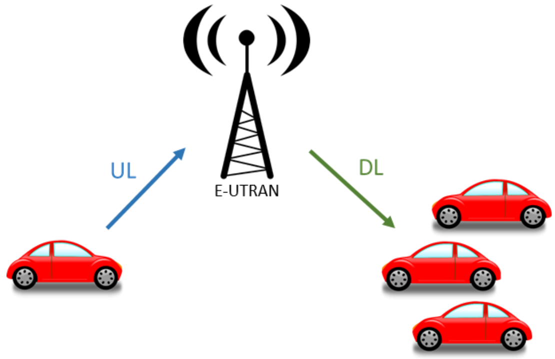

Figure 14. Uu based V2V

2. V2I operation based on PC5 (UE type RSU) / Uu (eNB type RSU)

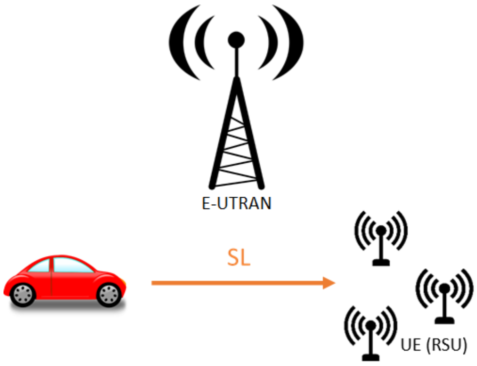

Figure 16. PC5 based V2I

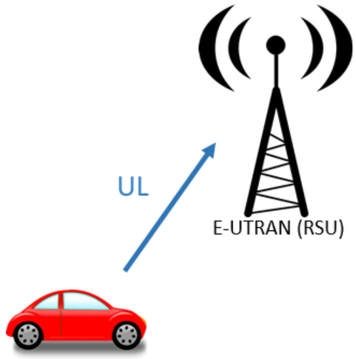

Figure 17. Uu based V2I

3. V2P operation based on PC5/Uu

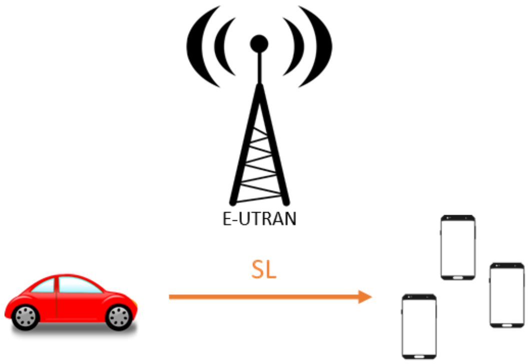

Figure 18. PC5 based V2P

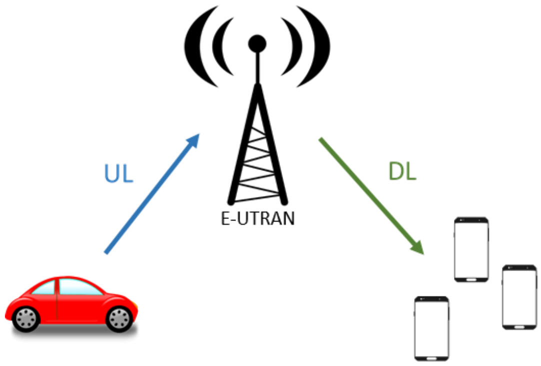

Figure 19. Uu based V2P

Multi-carrier operation scenarios

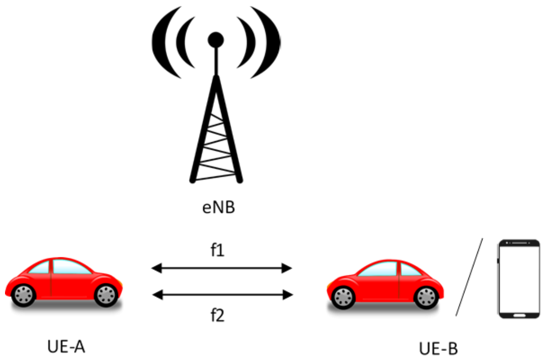

Figure 21. MCC operation at 5.9GHz (PC5 + PC5)

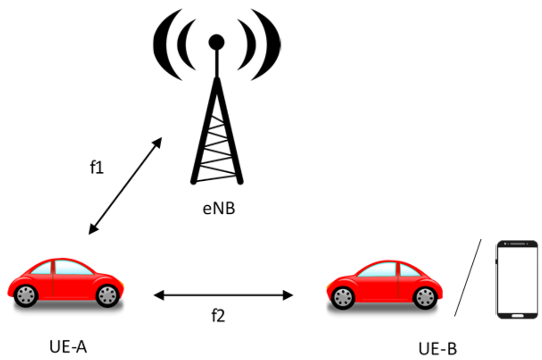

Figure 20. MCC operation at 2GHz + 5.9GHz (Uu + PC5)

SL: sidelink.

UL: uplink.

DL: downlink.

E-UTRAN: the initialism of Evolved UMTS Terrestrial Radio Access Network and is the combination of E-UTRA, user equipment (UE), and E-UTRAN Node B or Evolved Node B (eNB).

Appendix 3: LTE-V2X detailed architecture and data paths

The architecture of a LTE-A network is presented in the next figure. With this architecture, three V2X data path types can be considered.

In the first type, the distribution of messages uses the infrastructure and is controlled by the V2X server. Following a second type of path, V2X messages can be exchanged without the V2X server intervention, just routing the information from the sender VUE to the PDN-Gateway and from there to the intended receivers of the message in unicast mode. Finally, in a third data path type, the messages are exchanged between VUEs directly using the sidelink connection.

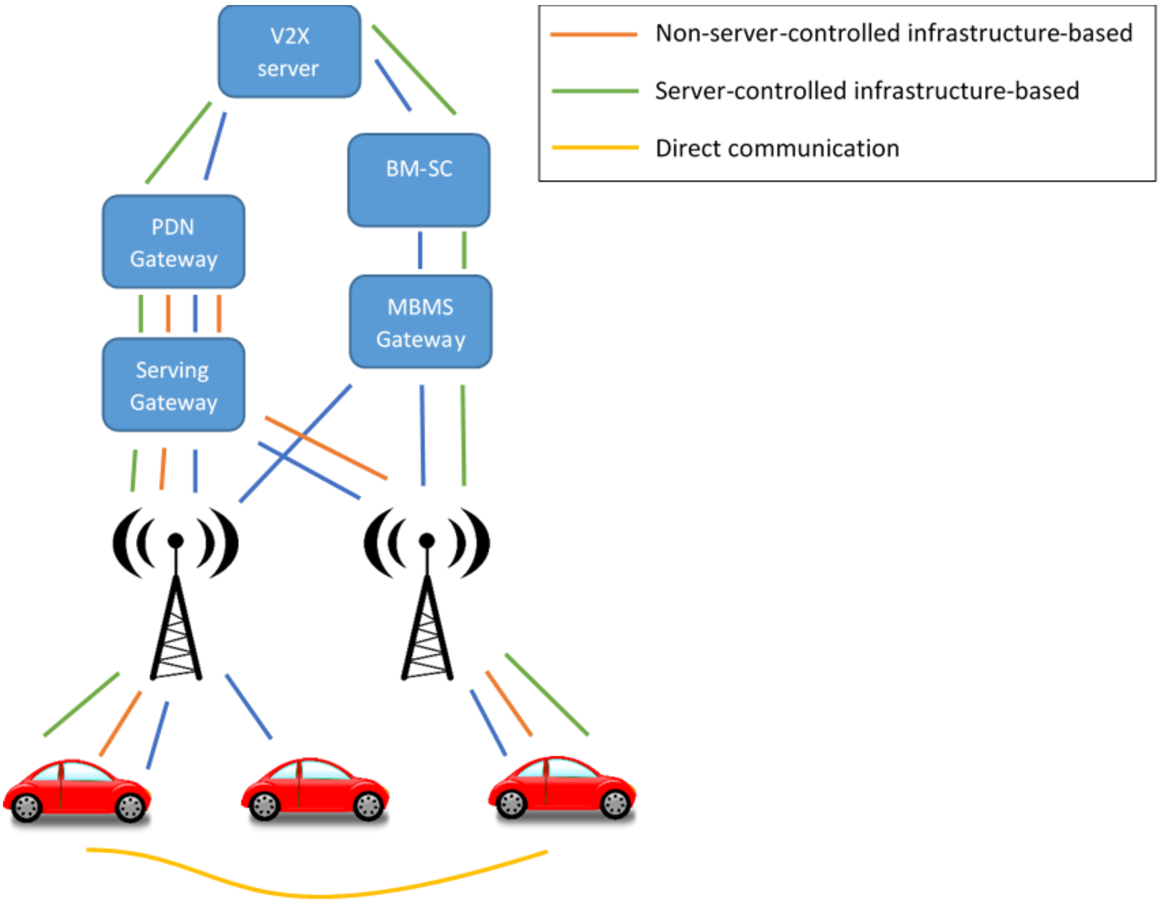

Figure 22. C-V2X architecture and data paths

Glossary

LTE

Long Term Evolution

SSCMOB

Sistemes de Suport a les Comunicacions Mòbils

AAX

Anàlisi i Avaluació de Xarxes

V2X

Vehicle-to-everything

V2V

Vehicle-to-vehicle

V2I

Vehicle-to-infrastructure

V2P

Vehicle-to-pedestrian

V2N

Vehicle-to-network

3GPP

3rd Generation Partnership Project

IEEE

Institute of Electrical and Electronics Engineers

ITS

Intelligent Transportation Systems

DSRC

Dedicated Short Range Communications

WAVE

Wireless Access in Vehicular Environments

OBU

On-Board Unit

RSU

Road-Side Unit

C-V2X

Cellular Vehicle-to-everything

QoS

Quality of Service

ETSI

European Telecommunications Standards Institute

CAM

Cooperative Awareness Message

DENM

Decentralized Environmental Notification Messages

HMI

Human Machine Interface

RWH

Road Hazard Warning

MAPEM

MAP Extended Message

RLT

Road and Lane Topology

MTU

Maximum Transmission Unit

TLM

Traffic Light Maneuver

SPaT

Signal Phase and Timing

SPATEM

SPaT Extended Messages

IVIM

Infrastructure to Vehicle Information Message

SRM

Signal Request Message

SSM

Signal request Status Message

TLC

Traffic Light Control

Wi-Fi

Wireless Local Area Networking

MAC

Medium Access Control

BSS

Basic Service Set

VANET

Vehicle Ad-hoc Network

TCMA

Tiered Contention Multiple Access

CSMA/CA

Carrier Sense Multiple Access with Collision Avoidance

CCH

Control Channel

VPKI

Vehicular Private Key

LDPC

Low Density Parity Check

GM

General Motors

UMTS

Universal Mobile Telecommunications System

CDMA

Code-Division Multiple Access

TDD

Time Division Duplexing

FDD

Frequency Division Duplexing

EPC

Evolved Packet Core

IP

Internet Protocol

ITU-R

International Telecommunication Union Radio Communications Sector

MIMO

Multiple Input, Multiple Output

eNB

Evolved Node B

RACH

Random Access Channel

ProSe

Proximity Services

MBMS

Multimedia Broadcast Multicast Service

MBSFN

MBMS Single Frequency Networks

SC-PTM

Single-Cell Point-To-Multipoint

GNSS

Global Navigation Satellite System

VUE

Vehicle User Equipment

SL

Sidelink

UL

Uplink

DL

Downlink

E-UTRAN

Evolved UMTS Terrestrial Radio Access Network

PDN Gateway

Packet Data Network Gateway

BM-SC

Broadcast Multicast Service Center

RB

Resource Block

TB

Transport Block

PSSCH

Physical Sidelink Shared Channels

PSCCH

Physical Sidelink Control Channels

SCI

Sidelink Control Information

MCS

Modulation and Coding Scheme

SPS

Semi-Persistent Scheduling

QPSK

Quadrature Phase Shift Keying

QAM

Quadrature Amplitude Modulation

DMRS

Demodulation Reference Signal

PLMN

Public Land Mobile Network

CBR

Channel Busy Ratio

CR

Channel occupancy Ratio

VRU

Vulnerable Road User

RAT

Radio Access Technology

CoCA

Cooperative Collision Avoidance

TeSo

Teleoperated Support

CLC

Cooperative Lane Change

LoS

Line-of-Sight

NLoS

Non LoS

NPP

Non-Preemptive Priorities

FCFS

First Come, First Served

TTC

Time-to-collision

UPC

Universitat Politècnica de Catalunya

GUI

Graphical User Interface