Update and Evaluate Vehicular Simulation Framework for LTE and 802.11p in OMNeT++

Master's Thesis
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Abstract

Today, the car industry has become one of the greatest users of both wireless and cellular technologies and is increasingly dependent especially in the area of wireless communication. Communication among vehicles is offering a lot of benefits and has testified improvement on safety, efficiency and possible automation of the traffic.

A lot of research has been focused on measurement campaigns, by investigating different situation for communication between cars in traffic. Lately, a hot topic is the simulation of the communication among cars and the environment. Therefore the focus of this thesis has been on advancing these simulation for IEEE 802.11p and Long Term Evolution (LTE) by performing updates with new modules and performance metrics.

One contribution of this thesis is exploring the simulation framework for DSRC and LTE known as VeinsLTE and performing updates to capture various environmental effects. These modules capture the attenuation effects on signal power caused by buildings, vehicles and other factors. Adopting the framework with these modules has offered a wider range for simulation and comparisons. Another aspect that this thesis has been focused on is V2V channel models, which are based on realistic measurements and make it possible to overcome some limitations of the simulation in different regions.

Computation of performance metrics such as delay and throughput has been achieved. These performance metrics offer another scope for analysis and comparisons among the technologies LTE and DSRC. Simulations will be focused on investigating different scenarios by covering various geographical regions such as intersections, roundabouts and highways. Comparison of the analysis results with realistic measurements results will given to the simulation results a strong validation.

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Contents

LIST of ABBREVIATIONS

VANET - Vehicular ad hoc network
ITS - Intelligent Transportation System
DSRC - Dedicated short-range communication
LTE - Long-Term Evolution
V2V - Vehicle to Vehicle
V2N - Vehicle to Network
V2I - Vehicle to Infrastructure
V2X - Vehicle to Everything
CP - Cyclic Prefix
LOS - Line of Sight
OLOS - Obstructed Line of Sight
NLOS - Non Line of Sight
C-V2X - Cellular-V2X
BSS - Basic Service Set
ITS - Intelligent Transportation System
FCC - Federal Communication Commission
OFDM - Orthogonal frequency-division multiplexing
RMS - Root mean square
EDCA - Enhanced Distributed Channel Access
ISI - Inter symbol Interference
EPS - Evolved Packet System
EPC - Evolved Packet Core
MMC - Mobility Management Component
S-GW - Serving Gateway
P-GW - Packet Data Network Gateway Component
UE - User Equipment
RNC - Radio Network Controller
DL - Downlink
UL - Uplink
DFT - Discrete Fourier Transform
PAPR - Peak to Average Power Ratio
VEINS - Vehicles in Network Simulation
SUMO - Simulation of Urban MObility
PLEXE - Platooning Extension for Veins
GUI - Graphical User Interface
NED - Network Description
TRACI- Traffic Control Interface

1 Introduction

Vehicles are evolving extremely fast as they are becoming more intelligent, efficient and safer and moving in the direction of automation [1]. This phenomenon is being supported by communication of vehicles with each other, known as vehicle to vehicle (V2V), communication of vehicles with the surroundings, known as vehicle to infrastructure (V2I), which in a broader aspect is being known as vehicle to everything (V2X) and is illustrated in Fig.1. Vehicle communication, where a lot of research is going on, is promising an evolved system for the traffic industry. Sharing information such as their speed, location and direction will help to prevent accidents in traffic. These data will inform the driver with warnings such as red traffic lights, or an upcoming car around the corner and assist in adapting speed based on the traffic flow. The aim is to create reliable communication with an increase in safety, efficiency, and stability.

A lot of attention is given to comparisons of various possible technologies for communication among vehicles. Dedicated short-range communications (DSRC) in the US and ITS-G5 in Europe, which both are based on 802.11p technology [2], are the main technologies for broadcast communication on V2V. Cellular communication technology has grabbed attention, especially during the latest releases of Long Term Evolution (LTE), which is known as Cellular V2X (C-V2X). LTE provides the ability to share data between the vehicles and the environment even in NLOS with distances larger than 1 km by making driving safer, more advanced and more efficient. Therefore, the combination of 802.11p technology and LTE technology would be one of the best alternatives for evolving the car industry through V2X communication.On the other hand, attention has increased in specific countries as China on cellular technology (C-V2X). The aim of this research is to create reliable communication with an increase in safety, efficiency, and stability.

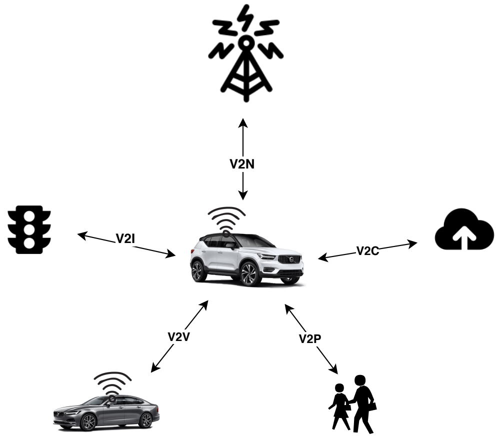


Figure 1: Communication of Vehicle with the surrounding such as Pedestrian (V2P), Vehicle (V2V), Infrastructure(V2I), Network(V2N) and Cloud (V2C)

During measurements in vehicle communication there exist limitations when increasing the number of vehicles for investigation, because this would require an increase in resources and hardware. The examination or the investigation of this data would require too much time and effort which sometimes would not be possible to handle. Therefore performing simulation would reduce the cost, time, budget, and resources by becoming a tool for analyzing and proposing a solution for the traffic industry.

There exist different environment platforms that supports simulations for vehicle communication with the necessary tools and freedom for extension of the existing implementation, but the most known are NS3 and OMNeT++ [3]. OMNeT++ will be used as the main environment platform in this thesis, since there exist more research on vehicular communication. Implementation of the 802.11p and LTE stacks is already done in OMNeT++. These frameworks offer the possibility for various network and vehicular simulation by using wireless communication technologuies. However, the implementation of the latest releases of the LTE stack has still not been completed for the OMNeT++ framework.

1.1 Objective

The aim of this master thesis is the advancement of the implementation of DSRC and LTE (VeinsLTE) in the OMNeT++ platform. Updating the framework for vehicular simulations with new models and features where the user can perform simulations for V2V and V2N would be very beneficial. Integration or computation of various performance metrics in the stack would be beneficial for exploring the differences between those technologies. Comparison of these two technologies through simulations with new models and performance metrics would make it possible to investigate their strengths and weaknesses.

A crucial point is considered that the framework should be rich with models and performance metrics in order to be able to investigate different geographical regions. This would make it possible to simulate scenarios in the same geographical region as in real measurements. This thesis should assist in overcoming some challenges for vehicular simulations and help in identifying issues and bottlenecks while evaluating modules used for simulation. Furthermore, the main intention of this thesis is to perform simulation that will offer a safer and better direction of vehicles towards automation.

1.2 Motivation

The increase of vehicle communication demands additional coverage especially in long-range non-line of sight scenarios that have driven the idea for a combination of wireless and cellular technology. This gives the possibility to use DSRC or LTE implementation stack in the base, depending on which one is more suitable for particular communication. The importance of LTE is because of the huge capacity that it offers, which could be used for exchanging non-safety information [4]. Besides the fact that LTE possesses higher quality and wider coverage, when it comes to delay, DSRC promises better results. The motivation has mainly been driven by the missing pieces in the framework from the scope of wireless communication. Looking from this side, some contributions to the framework would offer a more realistic point of view. Therefore work from this thesis has contributed in this aspect by advancing the framework for a better estimation of the simulation.

1.3 Contribution

The initial investigation brought up many ideas for the contribution of the framework for DSRC and LTE. The framework VeinsLTE that is used as a base has been published by authors in [5], which has been updated and investigated for various cases. As it was mentioned in Section 1.2, one contribution of this thesis is in the modules that have been found missing in this framework. The added contributions are the following:

1. Combining all existing modules into one. Updating the framework with the latest modules has been one of the first steps. Two modules for shadowing of the signal for DSRC for buildings and for vehicles and new realistic channel models have been imported and modified to work in VeinsLTE. Evaluation of those modules by bringing up their pros and cons has been performed as well.
2. Implementation of performance metrics in the stack of both technologies such as: delay, throughput, Manhattan distance. This contribution overcomes some challenges that users have been limited in simulating, by offering a new scope for analysis through simulations. Manhattan distance has been used for investigation of the Intersection scenarios.
3. Error Correction and control of the algorithm for decision making. Due to some randomness in the default decision making, re-modeling of the algorithm has been performed based on the need for analysis of each technology.
4. Analysis and comparison for four scenarios. Analyses related to various geographical regions have been performed by investigating and comparing received power, channel gain, delay, throughput. Comparison with realistic measurements on [7] have been illustrated for the intersection scenarios.

1.4 Limitation

The focus on the thesis was on providing a more realistic view of the framework VeinsLTE. Besides that, there are still many limitations on the overall system compared to how much better it can get. The thesis is restricted by the limitations of the modules due to the structure that was used when it was created. Another limitation is that all vehicles in a simulation possess similar behavior such as for example antenna height, pattern, attenuation of the signal and so on. It is important to mention that some of the modules may not be the best of their kinds, therefore we will try to evaluate them and bring up issues. An updated model for antenna pattern, which is important has not been possible to be implemented because of the missing library protocols on the default platform. The time limitation on the thesis has limited the implementation of models. However, evaluation of the used models will be performed followed by suggestion of new models for implementation.

2 Related work

There has been a lot of focus on measurement research for DSRC and LTE. This is an advantage for this thesis, since the simulation can be performed based on measurements. Therefore, in this chapter we will bring up various measurement analyses on these technologies from previous research. Exploring the benefits of those technologies for the simulation framework will be analyzed next, followed by an explanation of the VeinsLTE framework and the new modules that we adapted to this framework.

2.1 Measurement studies

A comparison of DSRC and LTE technologies is in the interest of this thesis, therefore the following analysis has been discussed. An assessment investigation between 802.11p and LTE(PC5) has been performed by 5G Automotive Association based on safety by comparing both technologies [8]. The report focuses on the packet delivery ratio and warnings for avoiding collisions. The report concludes that rural and urban environments are the most dangerous cases for collision. Based on this study when taking into consideration the cases that were studied, LTE(PC5) exceeds the performance of 802.11p by preventing more accidents, especially on high-speed roads.

On the other hand, Autotalks, in a report where comparison of both technologies has been performed, states that 802.11p beats LTE-V2X for safety applications [9]. Based on this document cellular technology has made a significant improvement for dealing with safety features in vehicle communication, but there is still need for improvement in order to outperform 802.11p standard. This conflict in results between documents relates to what is considered more crucial when comparing those technologies. Therefore, the use of both technologies is important and is considered as one of the best solutions. This relates to the scope of this thesis because similar simulation analysis will be performed on exploring the differences and benefits between both technologies.

2.2 Simulation research

Implementations on simulation frameworks for DSRC and LTE technologies have been performed previously. The implementation of DSRC which is known as Veins was performed in [11] and implementation of LTE known as SimuLTE has been performed by the group of the network department in [15].

These two frameworks have been combined together by Florian Hagenauer and his team, by creating a new platform VeinsLTE [5]. Creating a framework for the combined vehicular network has been achieved and the platform has been updated with the latest version in 2016. The framework itself brings a very good solution for heterogeneous communication. Even though there exist implementations of some of the modules and theoretical channel models such as the free space or two-ray models, what is missing in this platform is other propagation behaviors for what happens to the signal from the transmission node to the receiver node. This would include realistic channel models, reflections or shadowing by the environment such as buildings or other cars in the traffic. There exist many factors which would impact the signal power such as scattering, diffraction etc.

2.2.1 Exploring possible suitable modules for the framework

Screening and investigation of previous work was considered in order to find new modules for the framework VeinsLTE. Modules for different attenuation of the signal by the environment have been found in the Veins framework. These modules affect the signal by attenuating when buildings [13] and vehicles [14] are on the path of communication. Updating and adapting these modules to VeinsLTE was performed as an important step towards more efficient simulations. Furthermore, screening of the Plexe framework [12], which is used for platooning simulation with vehicles was performed, where a contribution with new realistic channel models was made by Christian Nelson at Lund University. These realistic channel models are highly important for having realistic simulations, therefore we have adapted them for use in VeinsLTE. While exploring the research area in this topic, there exist focus for research and simulation analysis. However, there has been no investigation based on the updated features that we will perform on this framework. This will be explained deeper when explaining the thesis work in chapter , where simulation of four scenarios and demonstrating the results was performed.

2.2.2 Exploring the necessary KPI's for evaluation of the simulations

Previous investigation for technologies DSRC and LTE was done and is being investigated at this moment as well. In [16] there is some investigation of the broadcast messages of DSRC. The same case follows LTE where a lot of research is being performed. However, research on these simulation frameworks has still not achieved the attention that it deserves, probably because of the complexity and the lack of instructions for modifying the frameworks.

In [17] there is an investigation of VeinsLTE that remarks on the challenges that the authors have faced while evaluating and performing simulations. They suggest more contributions to be done in the application layer, such as the investigation of the performance of delay, packet loss, and throughput. In this thesis that challenge is overcome since one of the contributions has been adding computation methods and analysis for the delay and throughput to the application layer.

3 Technical Background

3.1 IEEE 802.11p Technology

IEEE 802.11p represents an enhancement over the original 802.11 intended to be used for vehicular exchange of information. Dedicated Short-Range Communication (DSRC) is used for vehicular communication in the US, while in Europe ITS-G5 is used. The main perspective of these technologies is reducing traffic jams and preventing accidents. This is achieved by allowing exchange of data between different vehicles, which as a result brings a new standard in transportation safety [2]. A lot of 802.11p specifications such as physical and MAC layers are based on the existing standards of 802.11a. However, in 802.11p data can be shared between different nodes without being part of the same Basic Service Set (BSS), in other words, without the need for any authentication. Such implementation leads to less complicated and more efficient communication, by simplifying the BSS for better use in Vehicular ad hoc networks (VANET). In this way, managing of vehicle traffic for safety, parking, automotive repair, and localization through communication is more efficient. This assists in the so-called Intelligent Transportation System (ITS), which aims for an improved traffic flow by using wireless communication through V2V and V2I.

3.1.1 Direct Short-Range Communication (DSRC)

DSRC, which is also known as WAVE, uses a 75 MHz specific spectrum which was allocated by the US Federal Communication Commission (FCC) and operated in 5.9 GHz with the possibility of a communication range up to 1000 m. The FCC does not charge for this spectrum but it is limited by specific rules and restrictions. This spectrum of 75 MHz has been separated into seven frequency bands. DSRC is the same as other IEEE wireless standards but some changes have been performed on some of the layers in order to have a more efficient and adaptable system for vehicle communication [19].The protocol stack for DSRC depends on the IEEE 1609 WAVE structure. The receiver sensitivity controls the receiving signal and accepts only the signal that is above the set threshold. There are different minimum values of sensitivity based on modulation scheme and coding rate. For example, for a 10 MHz channel with QPSK modulation and a coding rate of 1/2 the minimum sensitivity is -82 dBm.

3.1.2 Channels in DSRC

In DSRC, OFDM with a 10MHz channel is used for data modulation in the physical layer, while in 802.11a, 20 MHz channel bandwidth is the standard. The use of a smaller channel bandwidth has several benefits, such as the possibility to overcome some cases for Root Mean Square (RMS) delay spread, since on a 20 MHz band, inter symbol Interference (ISI) might be present which leads to the necessity of using more advanced adaptive equalization algorithms [20]. While in the MAC layer [26], Enhanced Distributed Channel Access (EDCA) has been followed. The total spectrum for DSRC is separated into seven channels, which can be distinguished as a control channel (CH) and Service Channels (SH). Illustration of these channels and their differences is shown on Fig.2.

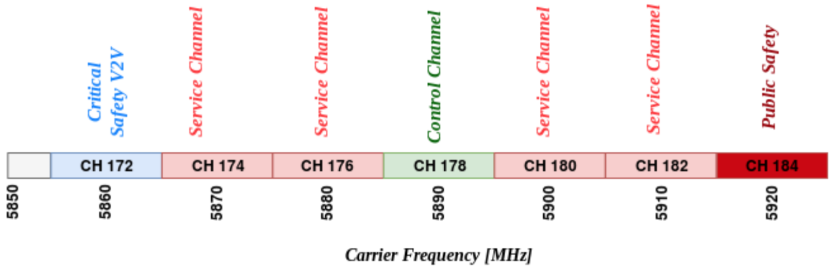


Figure 2: Channel types and spectrum in DSRC

Channels 180 and 182 are assigned for authorized agencies usage only. Channel 184 is designed for long range communication, which is required in certain cases. On the other hand, for safety applications channel 176 is assigned, and channel 178 would assist for controlled messages[21]. However, there is a strict rule that only a channel of 10 MHz bandwidth can be used and no other combination.

3.1.3 ITS-G5

ITS-G5 is a V2V communication standard at frequency 5.9 GHz that is defined for use in Europe. The focus is given to physical and data link layers, which are known as access layers. ITS-G5 supports new capabilities for managing the network and dealing with other communication issues. New features are included related to communication without BSS permission, therefore no security or safety control procedures are required [10]. Consequently, communication without the need for BSS permission will drive into disabling other features. Communication with ITS-G5 is specified into three different bands:

1. ITS-G5A is specifically defined for safety applications with the use of frequency 5,875 GHz to 5,905 GHz,
2. ITS-G5B is specified for non-safety applications and uses the frequency 5,855 GHz to 5,875 GHz,
3. ITS-G5D is specified for applications on frequency 5,905 GHz to 5,925 GHz,

An illustration of ITS-G5 architecture is clarified in Fig. 3. An important component that plays a major rule in the functionality of ITS-G5 is Decentralized Congestion Control (DCC). The DCC component assists in holding the stability of the network, equal distribution of the resources, restricting channel load, etc. Furthermore, DCC requirements limit the region boundaries where the communication takes place.

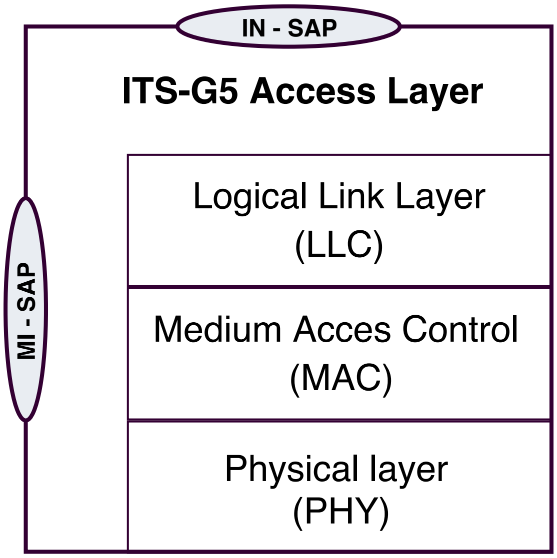


Figure 3: Architecture of ITS-G5, source: [10]

3.2 Long Term Evolution (LTE)

The vehicular technology of 802.11p has a limited range of communication with infrastructure, therefore, an alternative solution becomes essential to be used for vehicular communication. The need for high bandwidth, good quality of service which would include downloading, uploading, video streaming and accessing the cloud makes LTE a good choice to be adopted. However, there is still room for research when it comes to traffic safety application and emergency messages. One of the major issues is latency that is introduced into the system due to the fact that all communication has to pass through the base station. Lately, a lot of focus has been given to C-V2X and the use of unlicensed spectrum for D2D communication, for which standard has been introduced in [22].

3.2.1 LTE structure

Development of LTE started with release 8 and has been continuously advanced up until release 14 which was introduced in 2017. Different requirements were defined and met by each release which leads to a quite advanced system architecture and an evolution of the eNodeB. LTE radio access is known as E-UTRAN which consists of eNodeB and User Equipment (UE). The Evolved Packet System (EPS) does not support circuit switching but rather works only with packet switching. The EPS consists of E-UTRAN and Evolved Packet Core (EPC) [23].

The main task of the EPC is supplying IP based connection.The EPC is built from a Mobility Management Component (MME),a Serving Gateway (S-GW) and a Packet Data Network Gateway Component (P-GW).The MME's task, besides a Leading Control Component is also security. Meanwhile, the S-GW and P-GW are mainly responsible for handling data transportation to the User Equipment (UE). The operation and structure of LTE are shown in Fig.4.

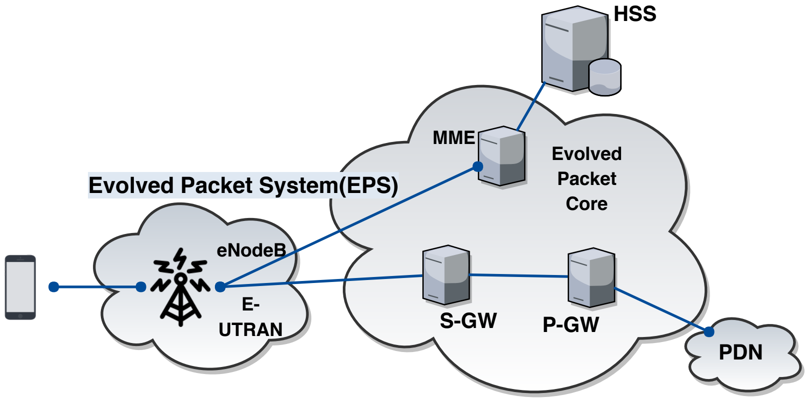


Figure 4: Structure of LTE

3.2.2 Evolved Node B (eNodeB)

The Evolved Node B (eNodeB) is what the E-UTRAN consists of and handles receiving and sending the radio signal to User Equipment (UE) and includes functionality for packet-switching. The main task is to provide communication between the User Equipment (UE) and the Evolved Packet System(EPS). The ENodeB handles coding and decoding of user protocol information, and manages the duplicated messages reception. It contains few functions and it is managed by Radio Network Controller (RNC).

3.2.3 Transmission in Downlink (DL) and Uplink (UL)

Two variants of transmission schemes exist in terms of communication path direction downlink (DL) and uplink (UL). DL represents the link from the base-station towards the UE while the UL is the exact opposite direction of communication, namely from UE towards the base station. The need for high data rate transmission with reliable link quality in DL is met using Orthogonal Frequency Division Multiplexing (OFDM). OFDM is a highly attractive solution that overcomes different issues that were present in the past for cellular networks such as for example Inter-Symbol-Interference(ISI). Advantages of adopting OFDM for LTE are as follows:

1. Transmission bandwidth flexibility.

2. Cyclic prefix with OFDM systems which makes it gain a huge advantage over other schemes.
3. Suitable to work on both time and frequency domains using Discrete Fourier Transform (DFT) and inverse DFT.

OFDM is used as well for UL communication with some modifications applied in order to make it suitable for UEs operation. This led to the introduction of DFTS-OFDM where a pre-coder DFT processes the data prior to IDFT, which helps to lower the Peak to Average Power Ratio (PAPR) hence, efficient power amplifiers can be used in the UEs. Modulation techniques and coding are selected based on the radio interface conditions (SNR values), where mostly QPSK, 16QAM, and 64QAM are used, while Turbo coding and constitutional coding are chosen for the coding.

3.2.4 Cyclic Prefix (CP)

A cyclic prefix is introduced in OFDM systems by adding a copy of the last part of the OFDM symbol into the beginning. It plays a major rule in overcoming ISI due to multipath propagation. In order to avoid ISI cyclic prefix length needs to exceed the multipath delay spread as been illustrated in Fig.5. Different settings of CP are possible in LTE networks, and it varies based on environment and can be setup by a system designer.

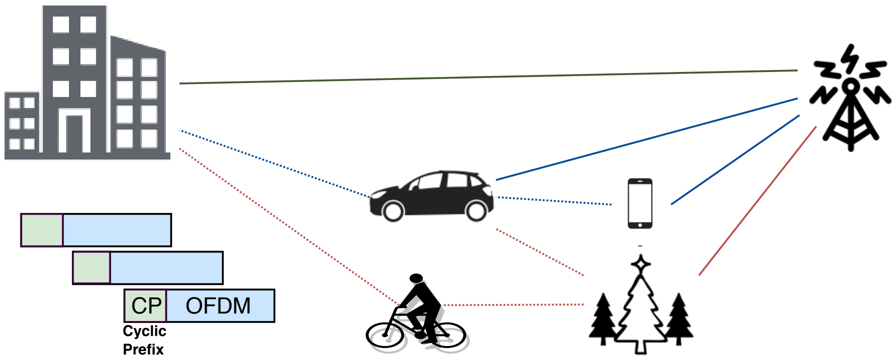


Figure 5: Cyclic Prefix in Multi-path Communications

3.3 Wireless channel models

Channel models describe various effects of a communication channel on wireless signals propagating from transmitter to receiver. In order to perform proper analysis and evaluation of the performance in large systems, a suitable realistic channel model choice needs to be carefully considered. Usually, these models are based on assumptions but are validated through field measurements. There exist different behaviors which characterize the effects of signal propagation through a wireless channel. Briefly, the most investigated behavior are signals reflection, diffraction, and scattering [24]. Generally, variations of the signal level due to attenuation can be expressed in two cases:

1. Large-scale fading refers to the loss on signal power with the increase of the distance traveled where large obstructions such as buildings or hills are blocking the signal path. These variations of Large-Scale fading have been investigated in this thesis when a building is obstructing the signal propagation causing attenuation and affecting the signal level.
2. Small-scale fading occurs because of the multipath propagation of the signal while traveling towards the receiver. These variations from the multipath propagation can be clarified by a constructive or a destructive interference. Variation due to Small Scale fading has not been investigated in this thesis.

For a good estimation for the channel model, it is crucial to grasp the geographical region covered, since different variations are applied based on the environment. Channel knowledge is significant for improving the received signal level by overcoming the impacts through techniques such as precoding. An estimation of a channel model considers obstruction of the signal by buildings, vehicles, ground reflection and other effects from the environment. There exist many channel models as different environments will have different multi-path components and effects. Some simple channel models are free-space propagation, two ray ground reflection etc. Free-space propagation assumes that no obstacles stand in the signal's path and the signal power only decays by distance. Free space path loss computation is shown in Eq. 1 where λ is the signal wavelength, and d refers to the distance from the transmitter to the receiver.

$$PLFreespace = 20\log_{10}\left(\frac{4\pi d}{\lambda}\right), \tag{1}$$

Two ray ground reflection is another model which estimates the behavior of the signal in a line-of-sight (LOS) case. This model describes the reflections made by the ground plane between two antennas that are at different heights. This model is especially important for base stations located on road sides.

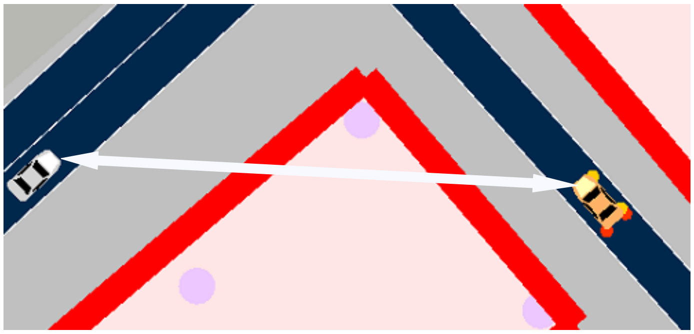
3.3.1 Vehicular channel model

In vehicle communication, the channel model is also essential for analyzing various environment impacts on signals. Same behaviors as in other wireless communication systems are also present on the vehicular channel. However, in vehicle communication the effect of the ground reflection is more present in LOS cases. Another important aspect of the vehicular channel is Doppler shift, which occurs when the vehicle that is Tx or Rx is moving. In V2V when both Tx and Rx are moving the Doppler effect is highly present with a lot of scattering. The vehicular communication channel can be distinguished in the following ways:

1. Line of Sight (LOS) is present when there are no objects which will affect the signal power between a Tx Vehicle and a Rx Vehicle.
2. Obstructed Line of Sight (OLOS) is present when an obstacle is slightly affecting the communication link between two vehicles.
3. Non Line of Sight (NLOS) is present in cases when the communication link is affected a lot by obstacles such as buildings or large hill.

(a) V2V Communication in Line of Sight(LOS)

(b) V2V Communication in Obstructed Line of Sights (OLOS)



(c) V2V Communication in Non Line of Sight (NLOS)

Figure 6: V2V Communication cases

4 Simulation Platform

Different technologies have been implemented as a simulation platform during recent years and the main attention was given on implementation of 802.11p technologies. LTE has been in focus recently, and the implementation of the stack has been performed on OMNeT++. However, these implementations come with their limitations. There exist different simulator platforms for simulation such as NS3 or OMNeT++, which have their pros and cons. OMNeT++ has been chosen as the main platform for this thesis, it offers a wide range of freedom for investigating and updating the previous implementation of 802.11p and LTE. A short introduction for the concepts of the frameworks Plexe and VeinsLTE, their similarities and differences in OMNeT++ has been shown in Fig.7.

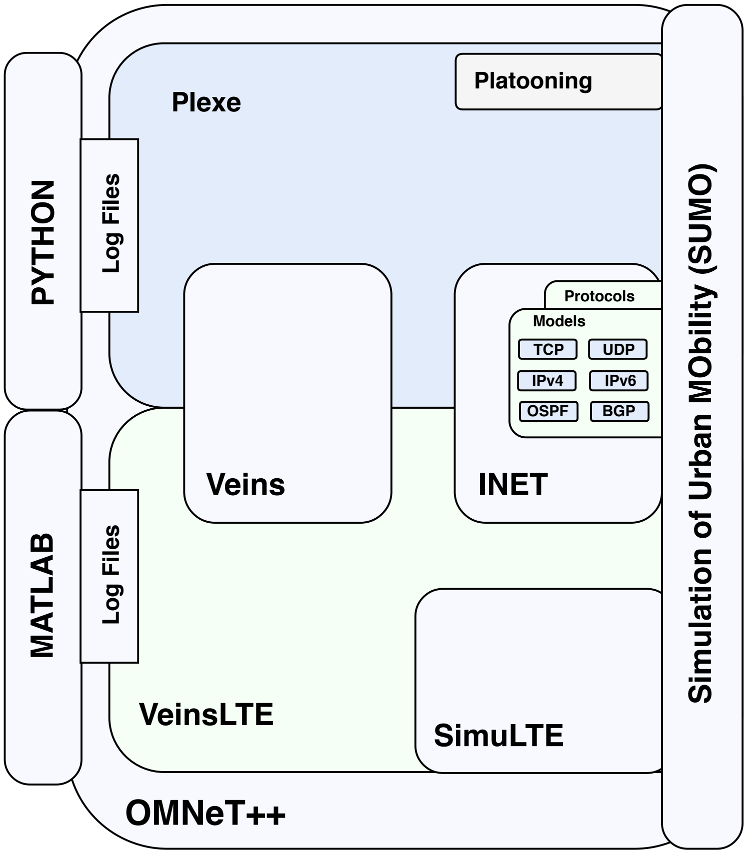


Figure 7: Relation among Plexe and VeinsLTE. Two independent frameworks VeinsLTE and Plexe that both use Veins and INET frameworks. The difference is that Plexe contains Platooning features while VeinsLTE contains the stack of LTE.

In order to understand the structure and how this system works together the relationship and architecture of each framework will be described. To avoid confusion between different terms the following is clarified:

1. Platform refers to the whole system and its features, such as OMNeT++ and the framework VeinsLTE which is the case in this thesis.
2. Framework refers to implementation of protocols, modules, layers or the whole stack. Veins, Plexe, VeinsLTE, INET are known as frameworks.
3. Module refers to features or models that exist and that are programmed through C++. Such modules can be defined as implementation of different protocols, libraries, channel models etc.

4.1 OMNeT++

OMNeT++ is considered to be a discrete network simulator platform, based and written on C++ libraries, with free licensed software for academic use. It provides the user with all the necessary tools and libraries for creating and performing simulations [3]. Modules are programmed in C++ and offer a good and wide assistance support through their documentation for different network and wireless operations. Modules and ideas can be reused for extending or creating new modules, this is due to the written structure which is simple and understandable compared to other C++ based software. Modules of OMNeT++ are connected via gates. This simulator platform is available for different operating systems as Linux, Mac OS, and Windows. The GUI offers a great feature especially if the user is interested in debugging or investigating what is happening behind the scenes. In addition, OMNeT++ with its own tool has the capability to analyze the data, which provides the user with a rich environment for performing various analyses and investigations.

4.1.1 Network Description (NED) File

The Network Description (NED) file is a very important file for OMNeT++, and handles various operations. Managing the connections between the modules is handled through NED files with support through the graphical interface or text mode. Changing from one mode to another is simple and beneficial. The graphical interface is more user-friendly because it consists of many tools which can assist in creating new modules, channels, and many other functions. Furthermore. when using text mode the source code of the NED file can be accessed and modified. The management of the connections, structures, the collection of the results and many other functions has been fulfilled by the support of NED files. The graphical user interface provides the user with a tool palette which offers many features for the modification of size, range, position, colors and other specifics.

4.1.2 INI File

The INI is an important file type which sets the parameters or configures the behaviours of the simulation. The configuration of INI files is performed by filling the configuration form or modifying the source code. It provides an easy way for setting and changing parameters of the simulation scenario or declaration of the commonly used variables. The INI file is responsible for defining the configuration of simulation parameters such as execution of the simulation in graphical or command-line interfaces, the size of the playground and many other specifications.

4.1.3 Result Analysis

OMNeT++ provides a graphical interface for analysis which offers the user a wide scope for investigation of data. The results are saved from the simulation as vector or scalar files. The recording of this information and the output has been performed with the combination of NED files, Header file, and C++ File. The results can be investigated as a bar, line or a histogram chart. Modification or changes to the result illustration can be accomplished such as adding a title, axis, legends and so on. If the user would like to re-run simulations with other specifications the same illustration of figures can be reused. Information data can also be added to a Dataset from which there is the possibility to sort, filter and create different groups.

4.2 INET

INET is considered the main protocol library for OMNeT++. It is composed of different features and modules such as the implementation of OSI Layers, transport protocols TCP and UDP, followed by support for the network stack of IPv4 and IPv6 and other various protocols for both wired and wireless links. Without the INET framework, it would be complicated to overcome some challenges of communication models in OMNeT++. Transferring messages is the way that this framework performs the simulations. INET support different components such as routers and switches, but also new components can be created by the user.

This framework provides a wide range of network protocols and other features. The modules that INET provides are considered to be well-structured thus giving opportunities to be modified and re-used for different purposes. INET is an open-source framework that is supported and kept up to date by the OMNeT++ community. Besides, INET can be considered practical and functional when creating new models. Other frameworks may need INET as a part of their system, while it is a favorable starting point for which the framework can be referenced. For instance, vehicular communication frameworks such as Veins use INET as part of their system, but similarly, other frameworks like SimuLTE consider INET as an essential part of their system.

4.3 Veins

Veins is the implementation of the 802.11p (DSRC) stack in OMNeT++ as an open-source software, with support for vehicular network simulation [11] . Veins offers an interface of collaboration between OMNeT++ and the Simulation of Urban Mobility (SUMO) simulator. In this way, by using OMNeT++ we are able to communicate on SUMO and to retrieve simultaneous feedback and updates for all events on the performed scenario. The architecture of Veins and relation with other frameworks is shown in Fig. 8.

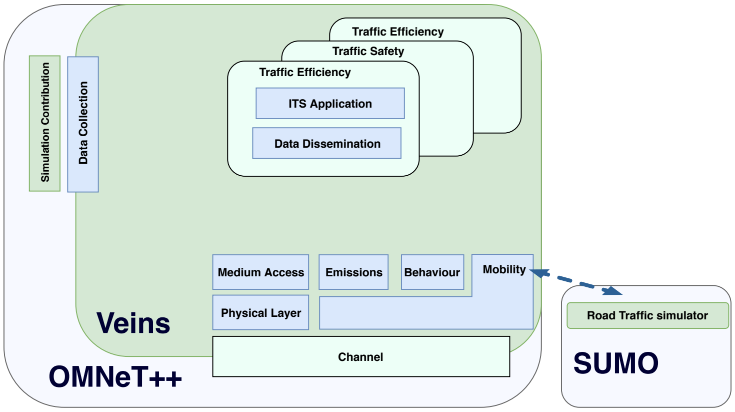


Figure 8: Architecture of Veins, source: [11].

Veins frameworks possesses different modules where various vehicular network simulations can be done. Veins can be well adjusted with the OMNeT++ platform and the SUMO simulator, which creates a complete simulation platform. In addition, it is responsible for modeling lower protocol layers, the configuration of the simulation, result gathering and mobility of the vehicles. The MAC layer has been integrated from the base of the IEEE 802.11p and IEEE 1609 Wave specification. Veins offers the possibility of shifting among control channels (CCH) and service channels (SCH) if the user finds it necessary. The default configuration uses control channels for simulation.

Generally, this framework contains many models and features for vehicular simulation, especially for IEEE 802.11p. Therefore the user should possess the necessary knowledge for executing the simulation because when the user is not aware of the right model one can incorrectly choose models that can be used for other intentions. To extend and perform certain simulations on Veins the user should possess knowledge for the use of OMNeT++, have a good understanding of the C++ programming language and be able to create new simulation scenarios with SUMO.

As mentioned previously, simulation is executing simultaneously on all three frameworks, Veins, OMNeT++ and SUMO. The last two are related to each other based on TCP connections and the protocol used for this communication is Traffic Control Interface (TRACI). Based on all this we can see the illustration of the mobility of the nodes from SUMO in OMNeT++. There have been updates of the framework continuously, new features have been added and errors or bugs have been fixed. Although all this work has been performed and accomplished there are still a lot of aspects that require improvements. New features can be added and there is always a demand for other investigations or contributions.

4.4 SimuLTE

The implementation of the Long Term Evolution (LTE) stack in OMNeT++ is an open-source software known as simuLTE [15], and it is performed by the Computer Networking Group at the University of Pisa in Italy. The framework provides tools for investigation of advanced systems for LTE network simulation as video streaming, VoIP etc. The programming language used for creating modules in the simuLTE framework is C++ and it uses the same module structure as OMNeT++. Overall, the whole simuLTE implementation contains approximately 40,000 lines of code. This framework supports communication with the Frequency Division Duplexing (FDD) mode for LTE and LTE-Advanced. It provides support on various cells, realistic channel model and some various types of antennas. In Fig. 9 it has been shown how the modules of User Equipment and eNodeB are implemented. Modules of the simuLTE framework have the ability to interact with each other and be connected to other modules as well. UDP/TCP and IP modules have been reused from the INET libraries. A description of the architecture of SimuLTE it is shown in Fig. 9.

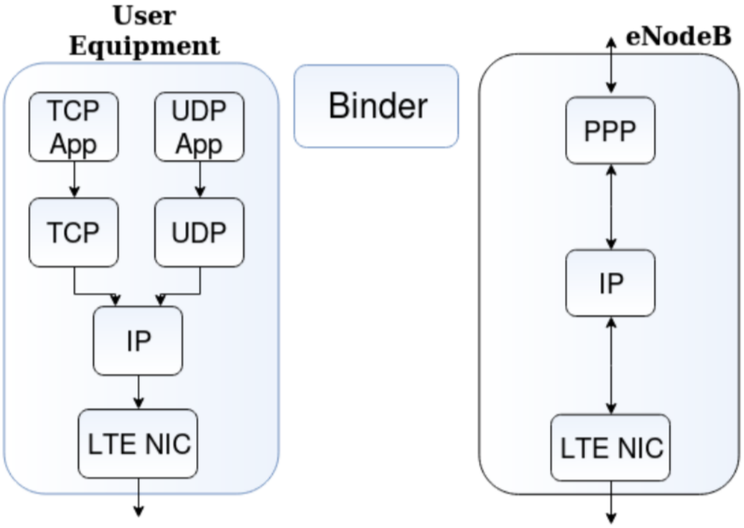


Figure 9: Architecture of simuLTE, source: [15].

Channel models that were used for validation of the framework are based on ITU Radio communication specifications. For more information about the structure of simuLTE refer to the document in [15]. Recently, there have been some updates of SimuLTE framework, but the new update does not support backward compatibility and it is still in the experimental phase for vehicular communication systems.

4.5 VeinsLTE

In general, 802.11p and LTE have their advantages and disadvantages and one preferable solution is often seen by the combination of these two technologies together. This was achieved by using the base of Veins and the unification with SimuLTE by F. Hagenauer [5]. An integration of Veins, OMNeT++, SUMO, and SimuLTE makes it possible for the user to execute heterogeneous network simulation. When performing simulation on VeinsLTE it is suggested to use of OMNeT++ 4.6 and SUMO 0.25. These version of OMNeT++ and SUMO are necessary in order to avoid compatibility issues for the user. The integration of SimuLTE has been challenging due to some restrictions of the SimuLTE framework, so new capabilities for adding or removing vehicles have been established. In Fig. 10, it is shown the interaction of the application layer and the decision maker.

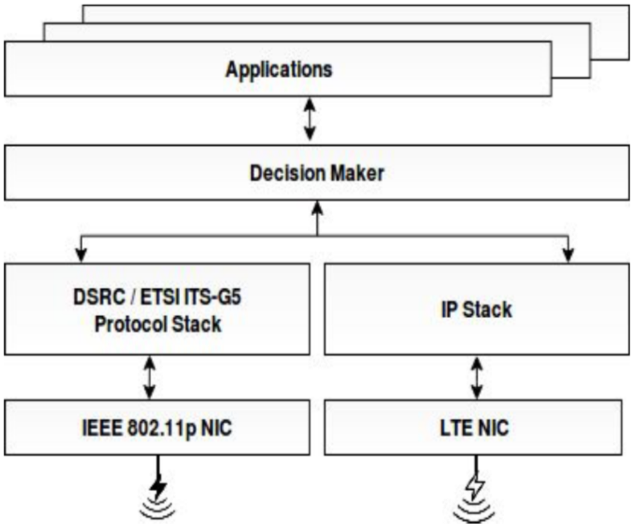


Figure 10: Protocol layers for IEEE 802.11p and Long Term Evolution (LTE), source: [5]

This interaction decides which technology will be used. If DSRC is chosen the beacons are sent through the 802.11p Network Interface Controller (NIC), while if LTE is chosen the beacons will be sent through the LTE NIC. In this way, this framework offers many possibilities for vehicular simulations for IEEE 802.11p and LTE. The default configuration for simulation is shown in Fig. 10, which demonstrates the structure of how the communication is performed.

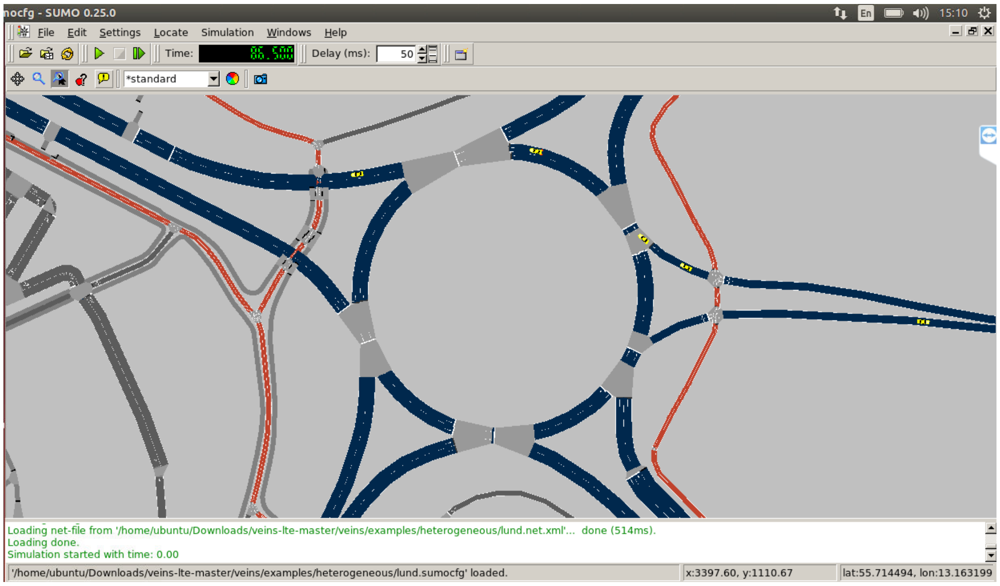
4.6 Simulation of Urban Mobility (SUMO)

Sumo is considered as a very important framework of this simulation platform. It is an open-source simulator with traffic designed for microscopic and high density traffic and has been created by the German Aerospace Center [25]. The implementation of this framework is done in C++, but for the modification of map scenarios with new vehicles and attributes, XML files are used. This framework supports a large amount of traffic specifics used for simulation. The mobility of vehicles can be independent from each other and specific configuration for each vehicle can be performed. It offers a wide range for simulation as follows:

1. Various vehicle movements.
2. Different vehicle types and environmental cases.
3. Adaptation to behaviours in the streets.
4. Traffic procedures and specifications.
5. Good performance of the graphical user interface (GUI).
6. Good performance for simulation with a large number of nodes etc.

SUMO has been used in many large and interesting projects and one of them is the simulation for Vehicle to Everything (V2X) communication. It offers support for simulation with Graphical User Interface or Command-line. This framework provides many traffic specifics such as traffic lights, streets, directions of the street and many other environmental specifications. The generation of traffic lights in the intersection or in other cases has different behaviors with the traffic lights in reality. This happens because the simulation uses algorithms for handling the configuration of traffic lights, even though this can be modified and adapted to real cases by changing SUMO files.

In SUMO we can import realistic maps and perform different wireless communication with the assistance of Veins and other frameworks and then observe the behaviors in the GUI. Importing the realistic maps for SUMO is performed by using OpenStreetMap files. This file can be converted with the assistance of various applications that are supported by SUMO into a package with files that SUMO understands. The creation of network file, polygons file, vehicles, and street can be performed by these applications in SUMO. In addition, for each vehicle different behaviors can be assigned like speed, distance, colors etc. In this way, we can control the traffic of the vehicles and investigate different environments. An illustration of a SUMO environment example is shown in Fig. 11.



```
Loading net-file from '/home/ubuntu/Downloads/veins-lte-master/veins/examples/heterogeneous/lund.net.xml'...  done (514ms).
Loading done.
Simulation started with time: 0.00
```

```
'/home/ubuntu/Downloads/veins-lte-master/veins/examples/heterogeneous/lund.sumocfg' loaded.
x:3397.60, y:1110.67
lat:55.714494, lon:13.163199
```

Figure 11: SUMO simulation environment scenario example

5 Methodology

This chapter describes the methods that have been applied in this thesis. The work which was performed is explained in more detail with focus on some of the contributions of this thesis. The methods and models which have been used are presented and the benefits of bringing these methods together. The chapter is divided into the following sections: combining existing modules to the framework, Implementation of performance metric's on the application layer for LTE and DSRC and the results that are obtained for analysis.

5.1 Combining existing modules into the framework

The framework VeinsLTE lacks some of the latest modules that exist in other frameworks such as Veins and Plexe. Those new modules have been cpntributed by different teams or authors by offering a wider and more realistic view for simulation. Therefore, an important contribution of this thesis is considered adapting all those modules to one framework. The main challenge in using these modules for the different frameworks is the lack of updates which is followed by no support for forward or backward compatibilities. However, in this thesis these modules have been reused and remodelled for VeinsLTE framework. The modules that have been adopted are: attenuation of the signal by buildings, attenuation of the signal by vehicles, and a realistic channel models for V2V communication. Those modules will be explained in more detail below.

5.1.1 Module for attenuation of the signal by buildings

Shadowing from the buildings is one of the main factors that contribute to the decrease of the signal performance. These effects are mostly noticed in cities which consist of many obstructions. Obstruction of the signal is explained in radio wave propagation theory [24]. In addition, penetration of the signal in streets with large buildings is also known as wave-guiding. The estimation of this model is based in measurements that investigate the attenuation of the signal by buildings and more information can be found in [13]. Therefore when there is a large obstruction of the building in the communication path, the receiver's signal goes below the threshold. The communication between two vehicles in a large distance and non-line-of-sight case will drop because of the receiver sensitivity parameter that has been set. Activation and deactivation of this module can be performed in the file config.xml where the user can modify the parameters for attenuation of the signal by buildings. As was mentioned in Section 4.1.2, the INI file will be used to configure this model for simulation.

5.1.2 Module for attenuation of the signal by vehicles

Attenuation of the signal power occurs when a vehicle is blocking or obstructing the communication link. This attenuation of the signal power has been modeled based on [14], which has investigated these effects of attenuation by vehicles. The module works only for OMNeT++ 5.0 and does not support backward compatibility for previous versions. VeinsLTE works on OMNeT++ 4.6 which is the suggested version by the authors in [5]. Therefore, rewriting this module for attenuating the signal by vehicles in VeinsLTE was challenging. Source code has been modified in certain cases and adapted to VeinsLTE. The implementation of this module for VeinsLTE makes it possible to capture the effects on signal power when the signal is obstructed by a vehicle. However, based on the previous research and during our investigation when performing simulations, we can conclude that this is not the best model for estimating the attenuation of the signal by vehicles. The module shows irrelevant results when we have a truck in front of the car or in a large number of cars. This can be noticed when we compare the simulation results with the measurements results in Yngve intersection in Chapter 7.

5.1.3 Module for realistic channel models

Another important aspect of this thesis is adopting realistic V2V channel models to the framework VeinsLTE. Realistic channel models that are based on measurements will offer a better estimation of the signal power at the receiver side. The realistic channel models that have been adopted to VeinsLTE are the so-called AutoCorrelated Two-ray V2V channel model and AutoCorrelated Single Slope channel model which has been modeled by the authors in [6]. These models have been a contribution by Christian N. on Plexe simulation framework which supports platooning (car following the lead) through DSRC communication. We have imported these channel models for DSRC by adding their features and adapting them to work with VeinsLTE framework. Furthermore, channel model for NLOS case have been integrated with the framework through the Matlab script and simulations have been performed.

5.2 Implementing performance metrics for DSRC and LTE stack

The default version of VeinsLTE offers some performance metric's that can be investigated in OMNet++ when simulations are executed. Various results are output from different layers of the implemented stack, but do not attract the interest of this thesis, since the focus here is on performance metrics at the application layer. Therefore implementation of these performance metrics has been one of the main contributions of this thesis. Important performance metrics that have been coded and implemented in C++ are the computation of received power, distance, Manhattan distance, delay and throughput. Even though OMNeT++ is rich in tools for analyzing the results, there exist some limitations. Therefore, for better analysis in this thesis we introduce our own log files which will be located on a folder called mylog that is found together with the files of the current simulation in the same place with the result folder. The computed results that have been in our interest have been saved in this folder and later has been analyzed with Matlab scripts.

5.2.1 Received power

Received Power refers to the value of the signal power which is measured at the receiver side. The transmitted signal power propagates from the transmitter to the receiver and degrades with distance. Received power for V2V through DSRC communication is calculated and saved to our log-file from the source code of Decider80211p.cc, which is located at the physical layer. This value of the received power represents the exact value of the RSSI because it includes all attenuations added such as building attenuation, vehicle attenuation and the channel model. Received power for V2N for LTE communication is found in the LteRealisticChannelModel.cc. The received power from the LTE channel model includes estimation of attenuations from the environment and this refers to the value of the RSSI. This channel model that is used for LTE is based on [18].

In order to have a well-structured investigation of the results and analyze what is happening in each event of the simulation the output of the received power will be followed by the output of simulation time. The results from received power can be illustrated in the OMNeT++ analysis or the raw data are saved in "mylogDSRC.txt" in the log folder "mylog". The same is done with LTE where the received power has been saved for both uplink and downlink.

5.2.2 Distance

By distance we are referring to how far the signal propagated from the transmitter to the receiver.This is an important value for the measurements, because the signal power decreases as the distance increases. Distance in our framework has been computed by obtaining the location of the transmitter and the receiver coordinates in SUMO. This computation is performed on the channel model and it has been saved for investigation.

Manhattan distance calculation is based on the Manhattan grid, and is mostly used for investigation of analysis in intersections. In this thesis, we have performed the computation of the Manhattan distance for investigating and comparing simulation results with the measurements results in [7]. Cordinates of the playground as for the vehicle x are (a,b) and for the vehicle y are (c,d) of each vehicle are obtained in SUMO.

$$ManhattanDistance = |a - c| + |b - d|. \tag{2}$$

Illustration of computation of Manhattan distance is shown in Fig.12. For analysis of the channel gain we have used our own log-files and created Matlab scripts for automation of the analysis.

5.2.3 Delay

Delay refers to the computed time that it takes from the transmission of a beacon message until receiving it. It is one of the main contributions and challenges on this thesis for both DSRC and LTE. Computation of the delay is performed in C++ and implemented in VeinsLTE for both technologies. The computation is

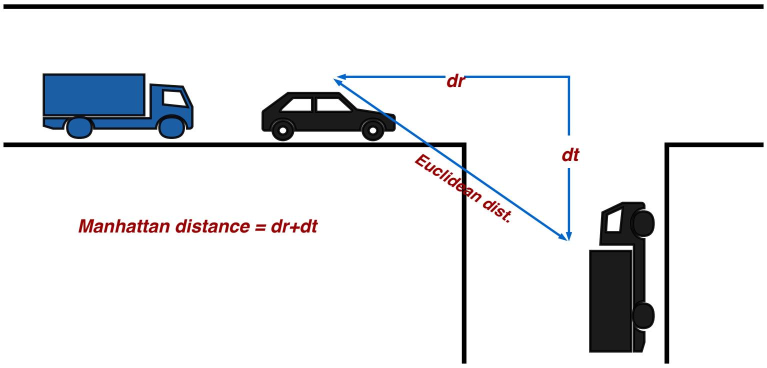
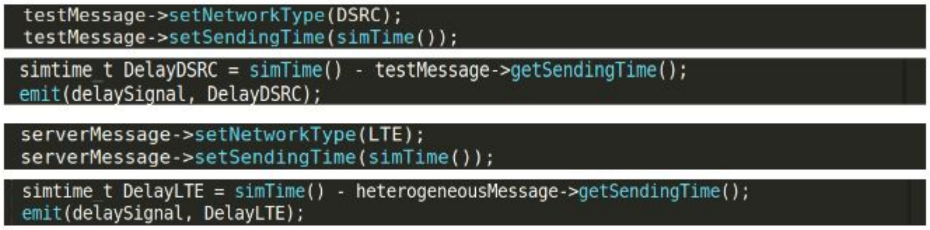


Figure 12: Computation of Manhattan distance in Intersections

initiated on the transmitter side when the sending time is embedded in each of the beacon messages that are transmitted. On the receiver side, we first find out if the received message is sent through DSRC or LTE and then compute the end to end delay. Computation is performed by removing the sending time from the arrival time as is shown in Eq. 3.

$$Delay = ArrivalTime - SendingTime, \tag{3}$$

For better understanding teh implementation snapshots of some of the code is illustrated in Fig. 13. After the computation of the delay for both technologies, the implementation for automated analysis of delay over simulation time in OMNeT++ was done.



```
testMessage->setNetworkType(DSRC);
testMessage->setSendingTime(simTime());
```

```
simtime_t DelayDSRC = simTime() - testMessage->getSendingTime();
emit(delaySignal, DelayDSRC);
```

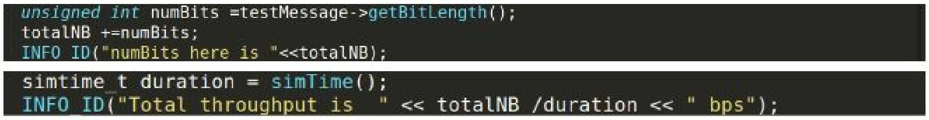
```
serverMessage->setNetworkType(LTE);
serverMessage->setSendingTime(simTime());
```

```
simtime_t DelayLTE = simTime() - heterogeneousMessage->getSendingTime();
emit(delaySignal, DelayLTE);
```

Figure 13: Snapshot of code for computation of delay

5.2.4 Throughput

Throughput refers to the total amount of data that has been sent between the transmitter and the receiver over the total time. Computation of the throughput for DSRC and LTE has been performed in the framework VeinsLTE. In DSRC communication, we first obtain the number of bits for each message that is being received. These bits will be added for all message that we receive in V2V communication and the total bits will be divided by the total simulation time. Implementation of the throughput through DSRC communication is shown by snapshots in part of the code in Fig.14.



```
unsigned int numBits =testMessage->getBitLength();
totalNB +=numBits;
INFO ID("numBits here is "<<totalNB);
```

```
simtime_t duration = simTime();
INFO_ID("Total throughput is  " << totalNB /duration << " bps");
```

Figure 14: Snapshot of code for computation of throughput in DSRC

In LTE the amount of data that has been received by the eNodeB is computed as this refers also to the amount of data sent to the vehicles. Computation of the throughput for LTE communication is performed by computing the total number of bits in LTE over the simulation time that the system takes to perform the simulation. A snapshot for the part of the code implementing throughput in LTE is shown in Fig. 15

```
unsigned int numbit =heterogeneousMessage->getBitLength();
totalNBLTE +=numbit;
```

Figure 15: Snapshot of code for computation of throughput in LTE

6 Simulation Setup

Simulation has been performed on a laptop which runs on Ubuntu 14.04. The simulator environment that is used is OMNeT++ 4.6, because it is more suitable for compatibility of libraries in these simulations. VeinsLTE is used as a vehicular simulation framework combined with SUMO version 0.25 and new features and methods which were explained in the previous chapter. An example scenario for communication of the vehicles through DSRC and LTE is shown in Fig.16

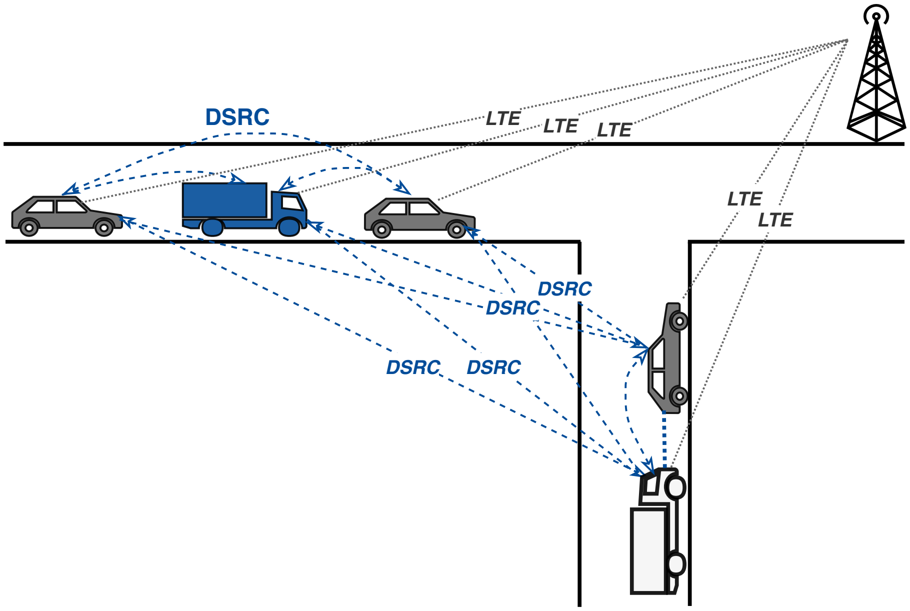


Figure 16: Simulation setup scenario for DSRC and LTE

Each environment differ from others, but the can be distinguished as LOS, OLOS, NLOS which are explained more in section 3.3.1. The channel model are based into these idea therefore the following cases are defined:

- Line-of-sight(LOS) case: V2V Two Ray LOS channel model is used when we have a clear LOS between two vehicles.
- Obstructed-Line-of-sight(OLOS) case: Single Slope Channel model OLOS are used for simulation when we have vehicles in the path of communication. As an alternative Single Slope LOS is combined with the model of attenuation of the vehicles.
- Non-Line-of-Sight(NLOS) case: Single Slope LOS channel model is combined with the module of attenuation by buildings which we call it as Combined model. However, NLOS channel model is a better estimation and is integrated for use through Matlab script.

6.1 Simulation Parameters

The parameters of the simulation are those that affect and control the behaviors of the simulation. These parameters are mostly defined in the omnetpp.ini file carrier frequency, receiver sensitivity, bitrate and Tx power. This follows other simulation features such as mobility, traffic channel model, vehicle and map specification. To change the beacon interval the user should locate the application layer in SimpleApp.cc. The parameters used when simulating for this thesis are chosen based on suggestions and restrictions from different regulations. More details for the parameters have been shown in Table 1.

Parameter	IEEE 802.11p	LTE
Packet rate	10 to 50 Hz	1 to 10 Hz, etc.
Packet size	10 to 1000 Bytes	10 to 1000 Bytes
Tx power(EIRP)	23 dBm	UE 25dBm, eNB 45dBm
Center frequency	5.9 GHz	2.1 GHz
Receiver sensitivity	-97 dBm	default
Data rate	6Mbit/s	default
Simulation Time	70s to 120s etc.	70 to 120s
Antenna height	1.5 m	25 m (eNodeB)
Path-loss Model	Two Ray, SSlope, NLOS	ITU-R (Rural, Urban)

Table 1: Simulation parameters for the scenarios

6.2 Simulation Scenarios

This simulation platform performs the ability to simulate various geographical cases and investigate different performance metrics. The work in this thesis provides the possibility for better analysis due to the new features and modules. Implementation of the performance metrics has been added also to the system analyzer of OMNeT++. In addition, Matlab scripts have been created to make it easier for the user to perform various analyses. The focus of the simulation has been driven into four scenarios:

1. Two intersections in Gothenburg city where simulations have been performed followed by computation of the performance metrics. The intersections are called “Yngve” and “Xerxes” and these two intersection have been chosen since there exist measurements [7] that were performed and on which we can base our simulation.

2. A roundabout in Stockholm has been chosen arbitrarily and used for simulation and performance investigation. This scenario was chosen as a suitable case to evaluate the obstruction of the signal power by vehicles in dense environments.

3. A Highway scenario that connects Gothenburg and Halmstad. The number of vehicles, speed, distance, and other performance metrics have been

investigated. The highway scenario is very beneficial for computation of delay and throughput for a large density of cars.

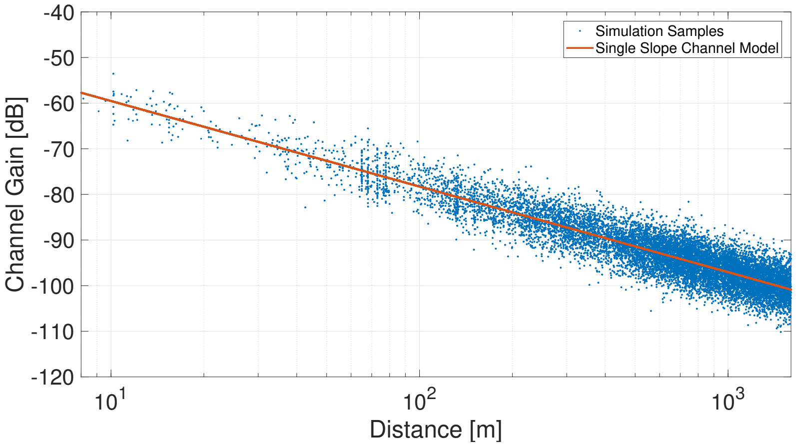
7 Results

In this chapter, we will show the analysis of results regarding performance metrics of LTE and DSRC technologies. Illustration of comparisons with real-time measurements and investigation between high and low dense cases etc. Scenarios such as intersections are more critical for vehicle communication, therefore they have been investigated. Furthermore, other geographical regions have been investigated and analyzed. This covers the most important cases of traffic such as intersections, roundabout, and highway. In addition, the focus of results will be on performance metrics that we have created such as received power, channel gain, delay, and throughput. The simulation has been run with different numbers of beacons/sec and the behavior has been examined. The intersections have a very critical propagation of the signal because of the effects from buildings, vehicles and the environment. The simulation will cover V2V communication through DSRC and V2I communication through LTE.

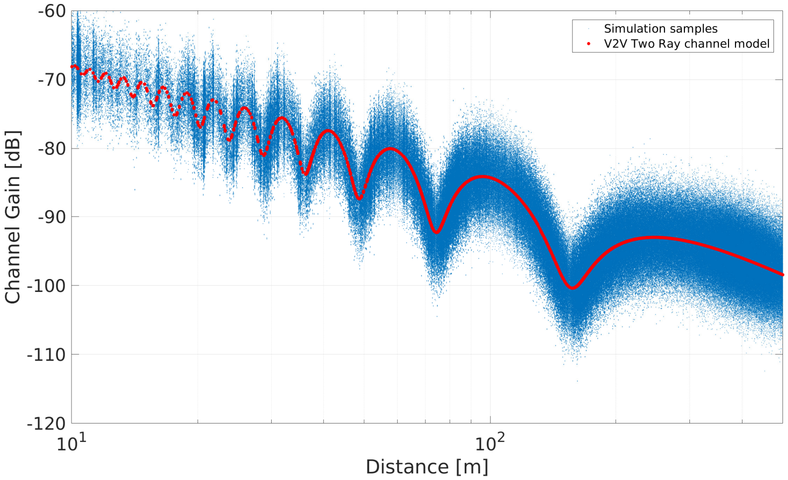
7.1 Validation of channel models

The channel models for LTE and DSRC have been investigated for validation purposes. In this way, it has been assured that channel models used for both technologies are valid and can be used for simulation. Channel models for V2V communication such as the two-ray channel model and the single-slope channel model have been shown in Fig.17. This was done to confirm that the adoption of the channel models has been successful. The behavior is similar also when comparing to the illustration of the measurement model [6], therefore we can say that the model has been successfully implemented.

The channel model for V2I communication through LTE has been demonstrated in the Fig. 18.



(a) Validations Single Slope Channel model in OLOS for frequency 5.9 GHz



(b) Validations Two Ray Channel model in LOS for frequency 5.9 GHz

Figure 17: Validation of the channel models for 5.9 GHz through simulations

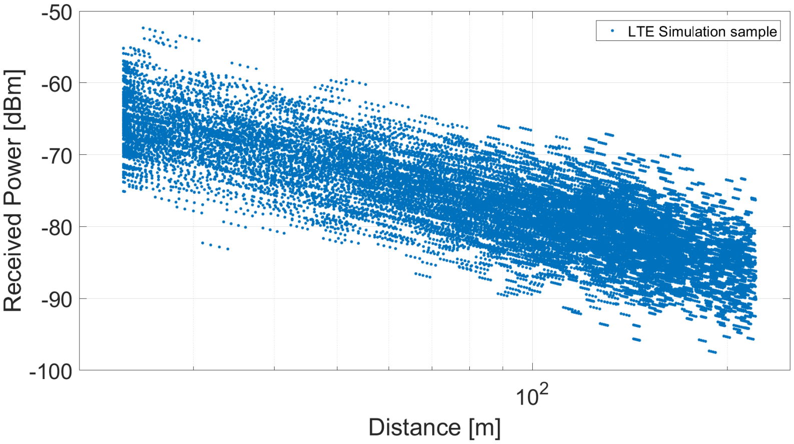


Figure 18: LTE Channel model for Urban Macrocell

7.2 Intersections

Urban intersection are very crucial point in V2V communication. Therefore, two intersection which are shown in Fig.19 has been analyzed in the simulations. Intersections Yngve and Xerxes are located in Gothenburg city and measurements which are performed on [7], with an outcome of a NLOS channel model. This model and other models that have been suitable are used for investigations and comparison by offering rich analysis to the the system. Location of base station for communication through LTE is at coordinates (57.701588,11.984744), which can be observed on the Fig.19. The simulations parameters are adopted based to the behaviors of the measurements but not the exact GPS coordinate.

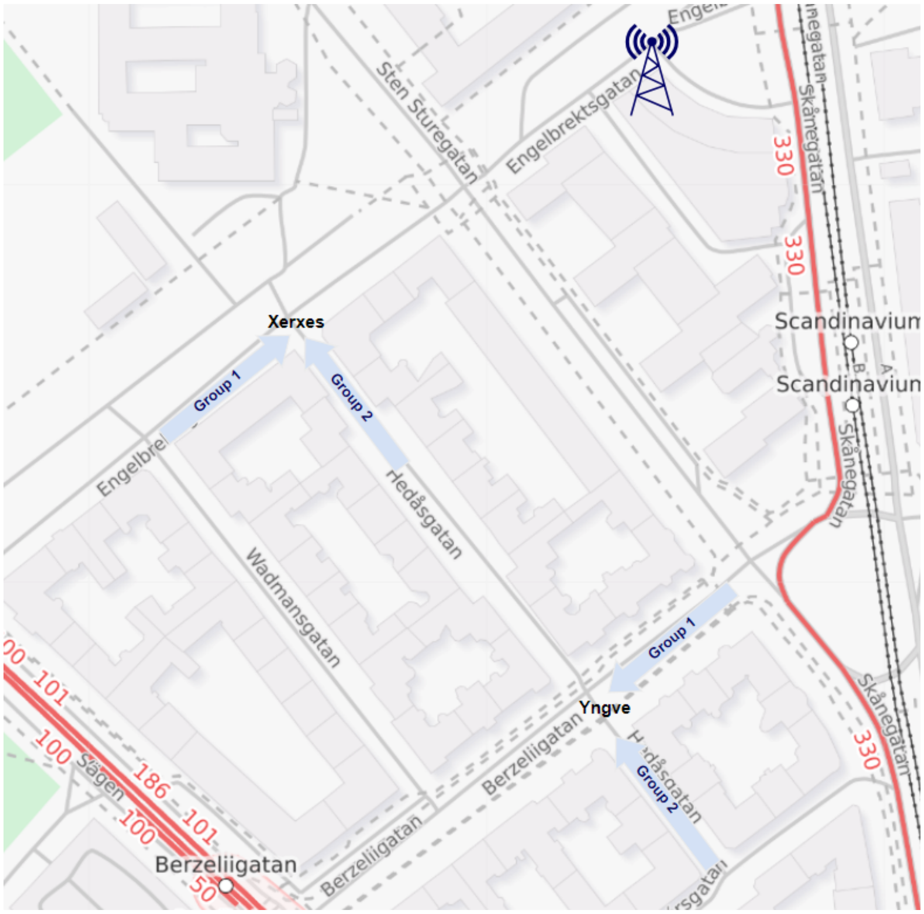


Figure 19: Intersection Yngve and Xerxes in Openstreetmap, in the right side of the map the base station for LTE communication

7.2.1 Yngve scenario

Yngve intersection is one of the main scenarios which we have used for analysis and evaluation. The simulation includes six vehicles divided into two groups with a truck between two cars. Two groups meet at the intersection point where there is LOS communication, while most of the simulation there is communication in NLOS case. A snapshot of the simulation between group 1 and group 2 is shown in the Fig.20.

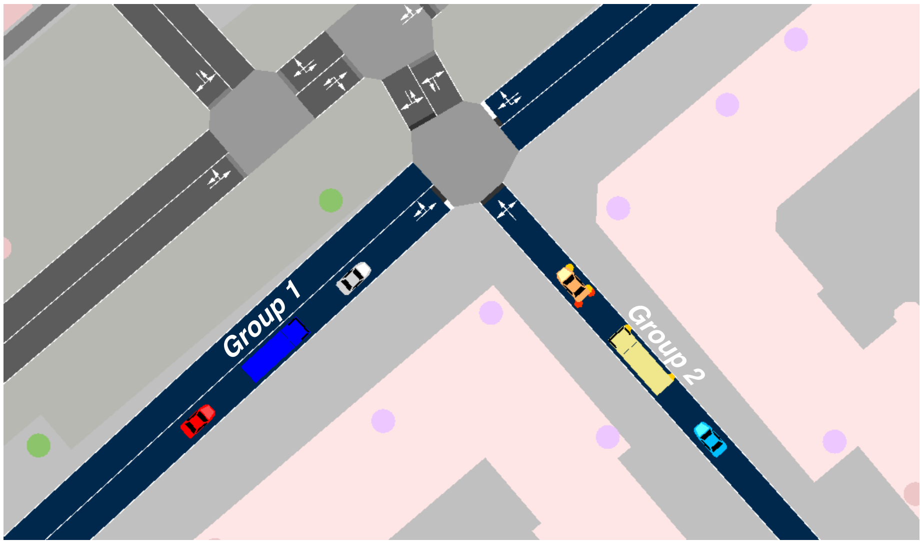


Figure 20: Illustration of the Yngve intersection from simulation performed through SUMO.

7.2.2 Received power over time

Received power over simulation time is illustrated in Fig. 21. We can observe from the figure how received power changes with time for the intersection Yngve. It can be investigated how the signal power is affected by the buildings, and the the environment. In Fig.22 communication between white car in group 1 and yellow car in group 2 is compared using Combined model and NLOS model. Received power of Combined model is very similar to NLOS model when the cars are closer to the intersection, while when communication happens in larger distance as in the beginning of communication there is too much offset between the two models.

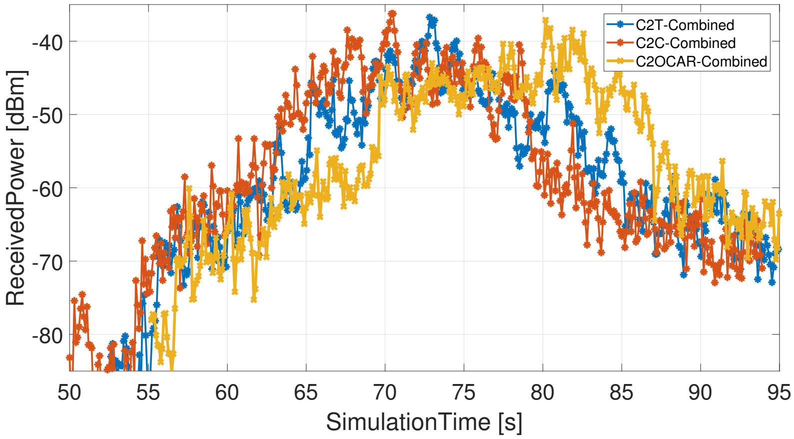


Figure 21: Average received power over simulation time using the combined model for communication in Yngve Scenario. Rx vehicle is in the group 1 white car from Fig.20 and TX is all vehicles in the group 2: yellow Car, yellow Truck, lightblue OCar.

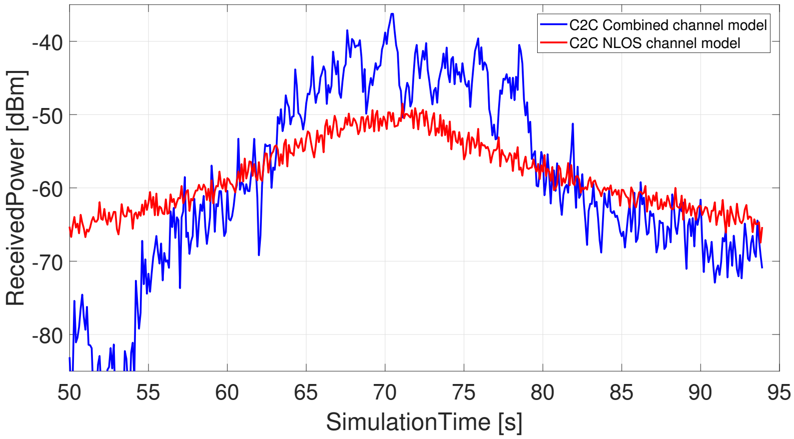


Figure 22: Yngve intersection, One Link communication C2C through Combined model and NLOS model.

7.2.3 Delay

An illustration of delay vs simulation time for LTE communication of one link Car2Network is shown in Fig. 23 and for communication between the cars through DSRC is demonstrated in Fig. 24. Communication between the two cars in this simulation occurs in 10 beacons/s in packets of 10 Bytes. It can be observed that the average delay for LTE is around 9 ms, while the average delay for DSRC is estimated to be 76 μs.

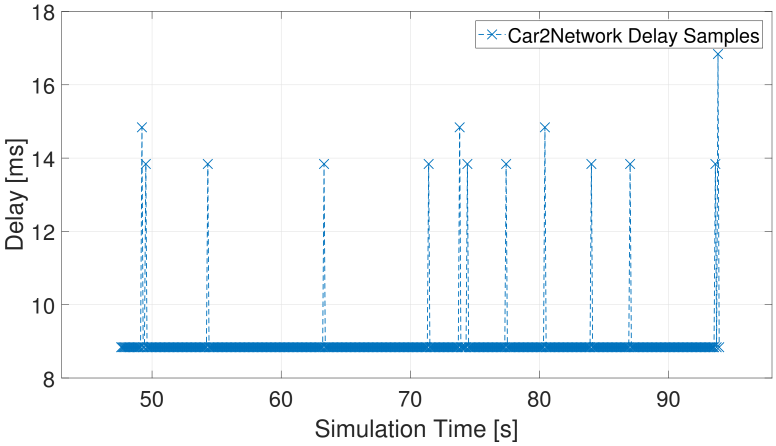


Figure 23: Delay for LTE in yngve intersection

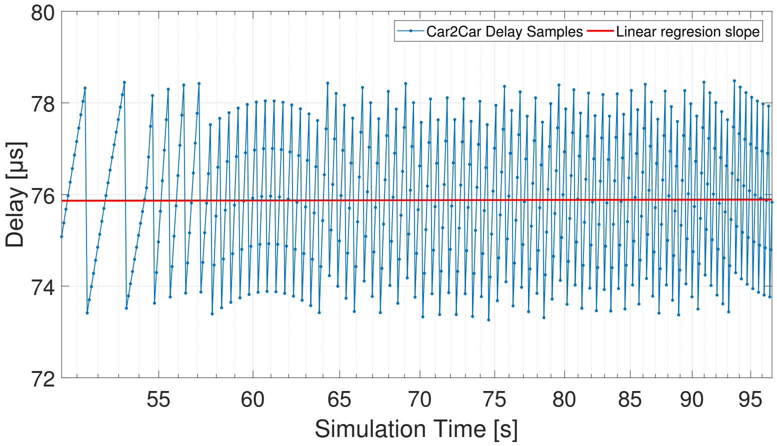
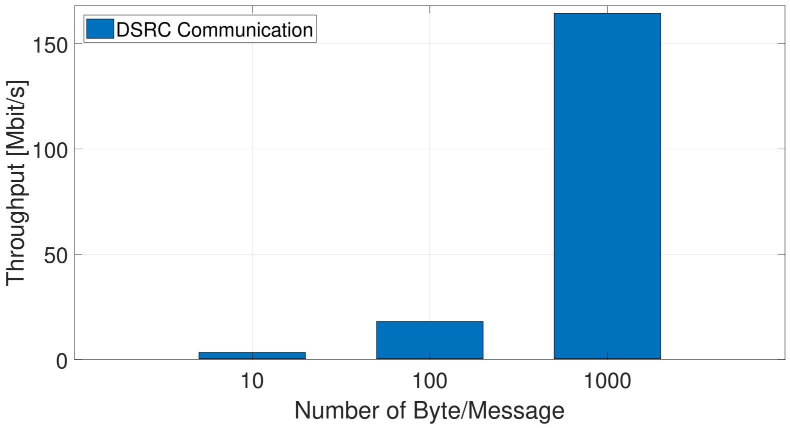


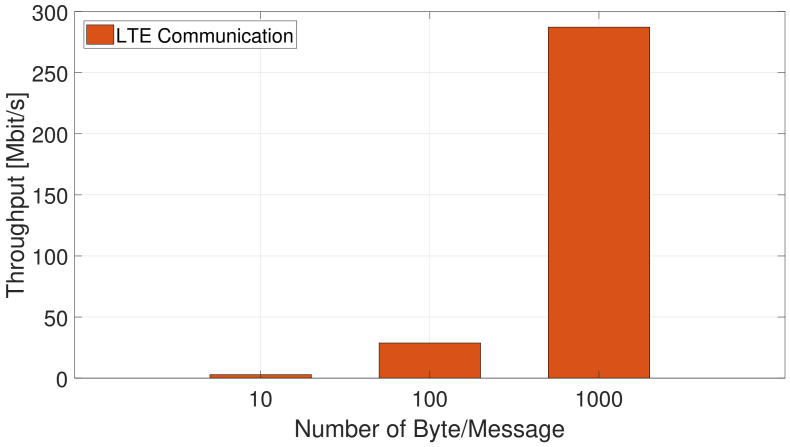
Figure 24: Delay for DSRC in yngve intersection

7.2.4 Throughput in Yngve intersection

Throughput for communication between two cars in Yngve through DSRC and LTE has been investigated in this section. Cars communicate in 10 beacons/s, where 10, 100, 1000 Byte per package has been sent in a period of 46 sec. Throughput comparison for both LTE and DSRC is demonstrated in Fig.25.



(a) Throughput for DSRC in Yngve Scenario



(b) Throughput for LTE in Yngve Scenario

Figure 25: Throughput of communciation between two cars (OneLink) for LTE and DSRC in Yngve intersection

7.2.5 Channel gain

The Channel Gain over Manhattan distance in Yngve scenario for communication between vehicles using Combined model has been computed and compared with the NLOS model from Nilsson et al. [7]. A demonstration of the simulation and the two groups has been shown in Fig.20. Base on that demonstration different simulations have been run and comparison has been perform with the Free space model, the NLOS model, and a sample of the NLOS model. In the communication between trucks we can conclude that the Combined model is in agreement with the NLOS model on distances smaller than 80 m, while for distances larger that 80 m the Combined model degrades faster. In the communication Truck2Car and Car2Car the model has some agreement as well for a limited distance, while for the communication of Truck with the ObstructedCar the model shows agreement on a distance smaller than 100 m. Based to this we can conclude that the Combined model is not suitable since have valid estimation only when the Manhattan distance between two vehicles in intersection is lower than 80 m. Furthermore, the implementation of the NLOS model would be a more advanced model for realistic simulation at 5.9 GHz.

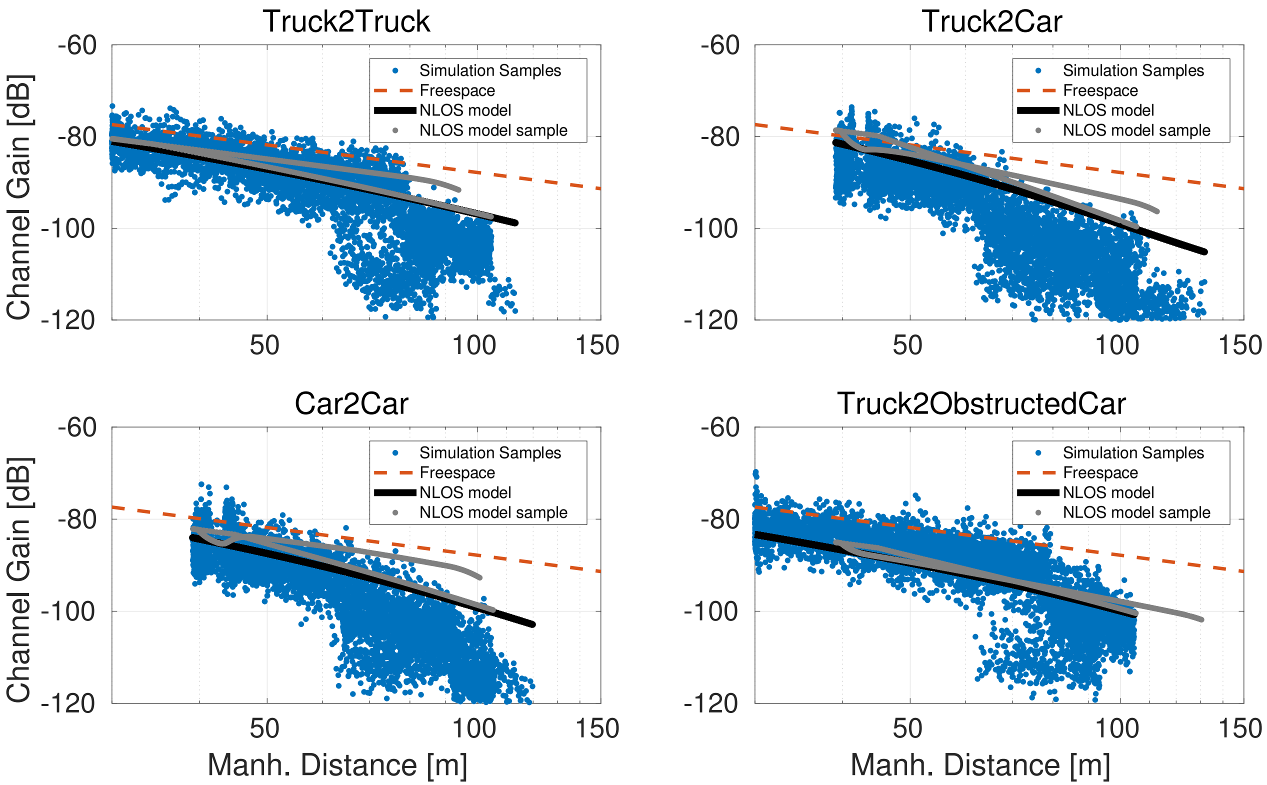


Figure 26: Channel gain over distance for yngve intersection

7.2.6 Xerxes scenario

Two groups of vehicles the same as in the Yngve scenario were simulated. They meet at the Xerxes intersection and continue towards their destination, as shown in Fig. 27. The vehicles communicate around the corner in a NLOS case, while when they are very close to intersection they have a clear LOS communication. The front cars of each group are noted as Car, then there is a Truck and the last car of each group is named as ObstructeCar.

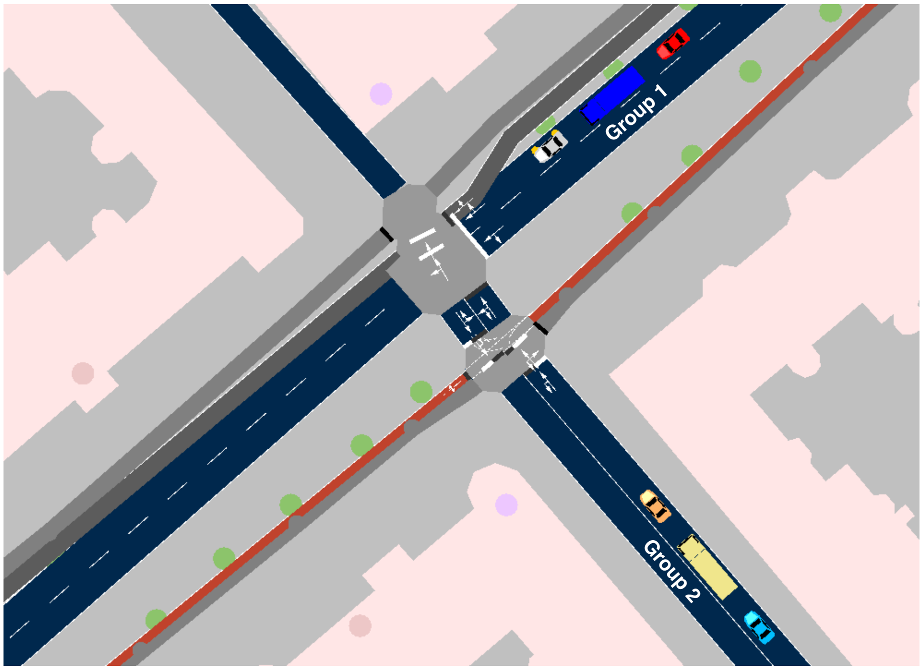


Figure 27: Snapshot of the Xerxes intersection simulations in SUMO.

7.2.7 Received power over time

The simulation of Xerxes provides measured received power at each moment and distance. Different communication links have been investigated using the average NLOS channel model, communication Truck2Truck, Car2Car and Car2ObstactedCar is demonstrated in Fig. 28. From the figure can be observed that vehicles met at intersection after 40 s. The NLOS model has been used in this demonstration, based on the conclusion from Fig. 26 in Yngve scenario.

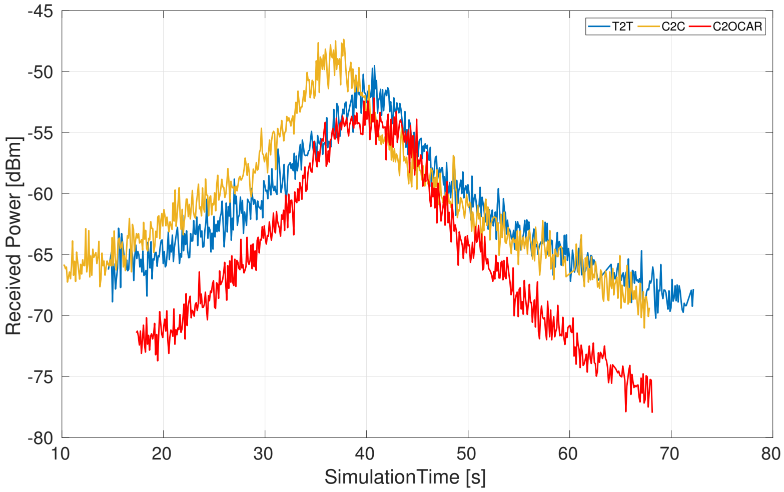


Figure 28: Average received power over simulation time in Xerxes intersection. Communication between Truck2Truck, Car2Car, Car2OCAR is illustrated where the Rx is the vehicles of group 1 and TX is the vehicles of the group 2.

7.2.8 Delay

The computation delay in Xerxes scenario for DSRC and LTE technology was simulated and analyzed. The computation is based on the parameters and behaviors that were explained above. The Communication uses 10 Beacons/s for both LTE and DSRC and as it is shown in the Fig. 30, for communication through DSRC there is less variation and better performance than with LTE technology. Delay samples represent communication between the white car of Group 1 with all the cars of Group 2.

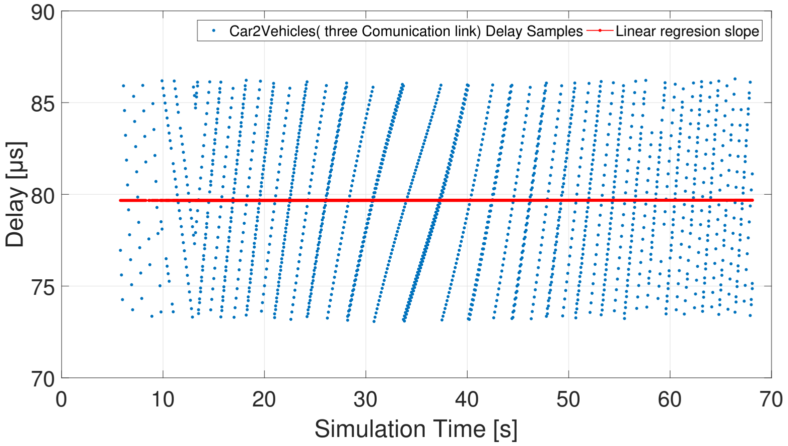


Figure 29: Delay of Car2Vehicles, Car1Group1 in DSRC communication with vehicles in Group 2 over simulation time.

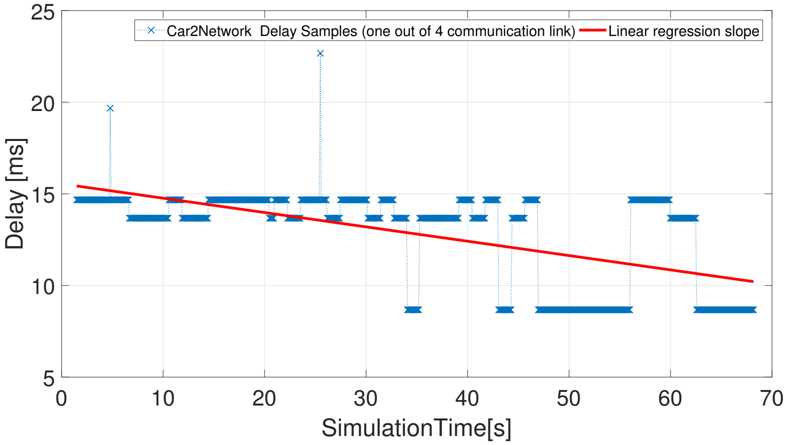
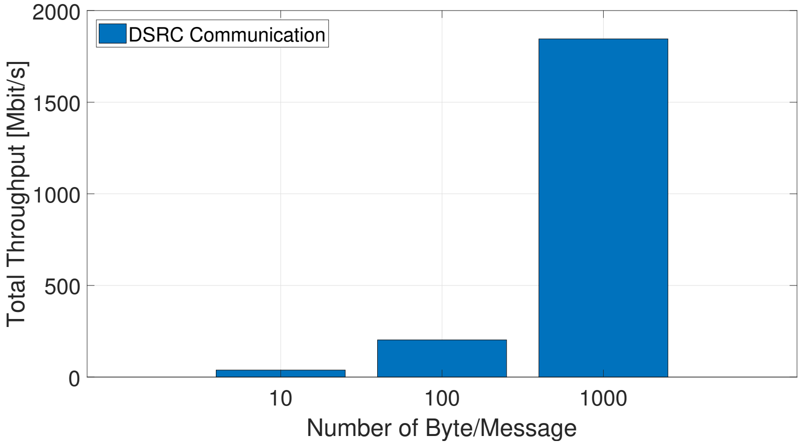


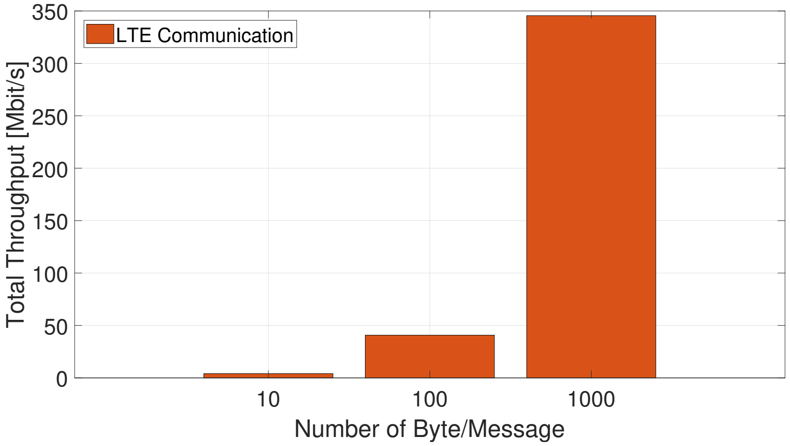
Figure 30: Delay for Car2Network,Car1 Group 1 in LTE communication with the base station in Xerxes intersection, one communication link out of four.

7.2.9 Throughput

Throughput in Xerxes Scenario has been investigated when communicating with 10,100,1000 Beacons/s for DSRC and LTE. Communication using DSRC is broadcast communication, therefore there is a lot of difference to the throughput in LTE.



(a) Total Throughput for DSRC in Xerxes Scenario.

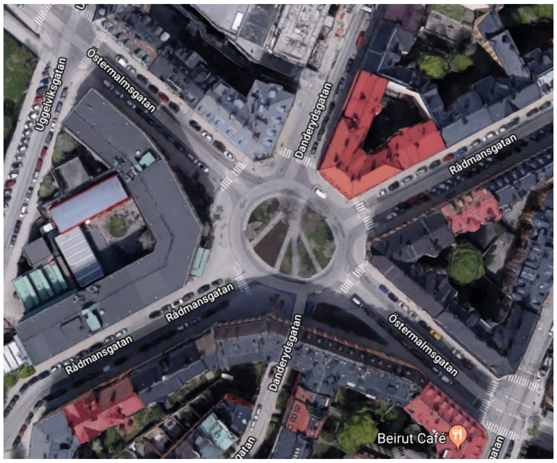


(b) Total Throughput for LTE in Xerxes Scenario.

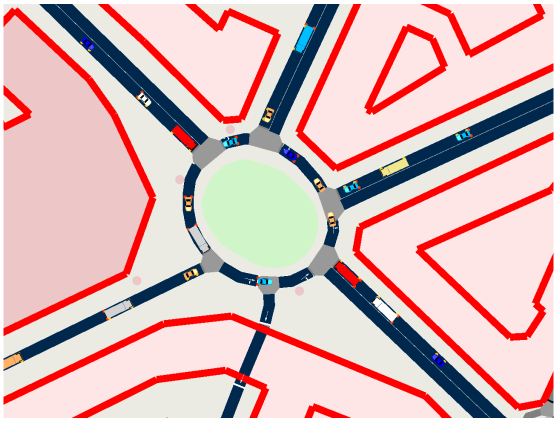
Figure 31: Total Throughput of communciation through six vehicles for LTE and DSRC in Xerxes intersection

7.3 Roundabout scenario

A roundabout is an important geographical region where the automative industry should focus as well. A lot of accidents occur in these cases during rush hours or dense traffic in large cities. Furthermore, the pollution on the dense traffic in roundabout seems to be more high compare to the other cases base on simulations. A roundabout that is located in Stockholm (lat 59.343641, long 18.070495) has been used for simulations. In this scenario analysis for C02 emissions,acceleration, Rx power and its effects by the vehicles have been in focus. The roundabout scenario that was used for simulations is shown in Fig. 32



(a) Snapshot of the google map for the roundabout in Stockholm



(b) Snapshot of GUI for simulations on Xerxes intersection

Figure 32: Roundabout scenario, a)Snapshot of the Roundabout from GoogleMap, and b) Snapshot of the roundabout simulation scenario in the SUMO

7.3.1 Received power over time

Received power for the roundabout scenario has been analysed to see the effects of the vehicle attenuation to the signal power. In Fig. 33 the samples of the Rx power with and without vehicle attenuations are shown. In order to view the difference and the effect of the obstructions of the vehicles the average received power is computed. The red line shows the average received power with vehicle attenuations and the blue line shows the received power without the vehicle attenuation. Vehicle attenuation shows good estimation when used for roundabout scenarios.

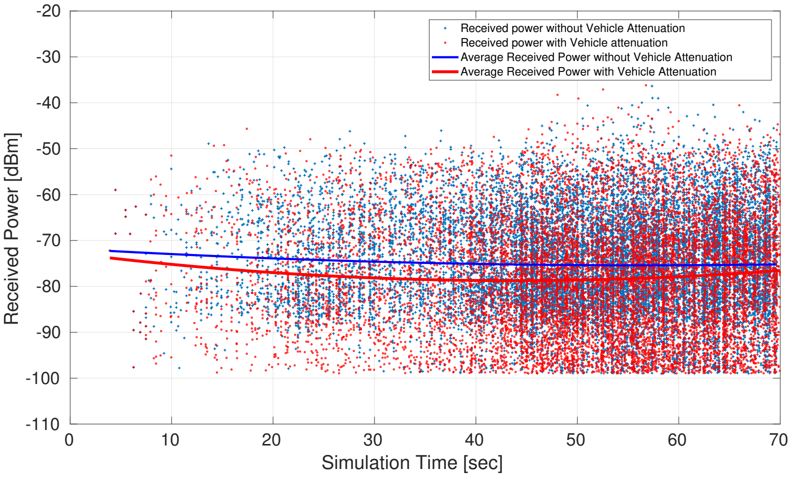
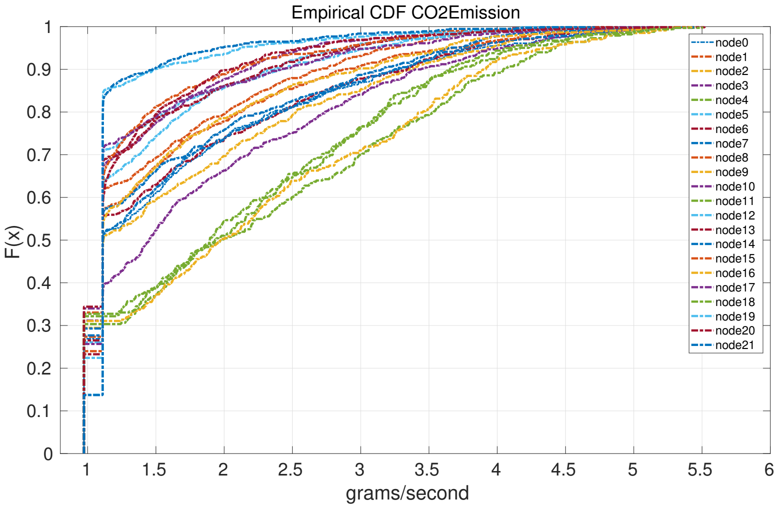


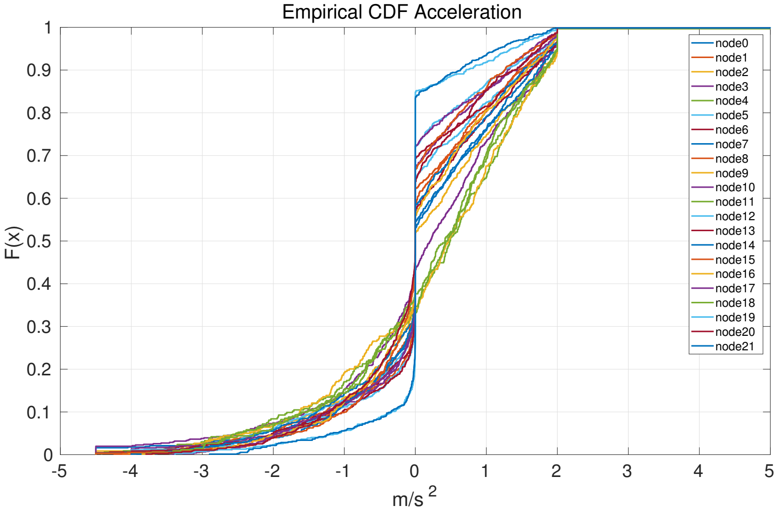
Figure 33: Comparison of Received Power with and without vehicle obstacle in roundabout scenario

7.3.2 CO2Emission and Acceleration

CO2 Emissions and acceleration have been in the focus of the roundabout scenario as well. A lot of pollution happens in large cities and roundabouts. Therefore, investigations and analyses should be considered for this kind of situation in order to improve and offer a better solution. CO2 Emissions followed by the acceleration results are illustrated in Fig. 34.



(a) CO2 Emission in Roundabout Scenario



(b) Acceleration for vehicles in Roundabout Scenario

Figure 34: Acceleration and CO2 Emission for vehicles in a roundabout scenario

7.4 Highway scenario

The simulation of this scenario is performed on the highway between Gothenburg and Halmstad. Vehicles are driving in the same direction and various densities of traffic have been simulated. The highway scenario has been seen as a good case for analysing delay and throughput results for various beacons/s and number of vehicles. As no building obstacles exist on the highway, this module is excluded and simulation has been performed only by including the vehicle obstacle model and the autocorrelated V2V channel models.

7.4.1 Received power over simulation time

The simulation of a highway with the communication of a large number of vehicles gives the result in Fig. 37. The comparison is done between the single slope model for OLOS and the single slope model for LOS plus the attenuation by vehicles. The model for vehicle attenuation performs well when communicating with a limited number of cars, but when the number of cars increases the model does not seem to have a good estimation. Therefore the channel model for single slope for OLOS in [6] should be used for a better estimation.

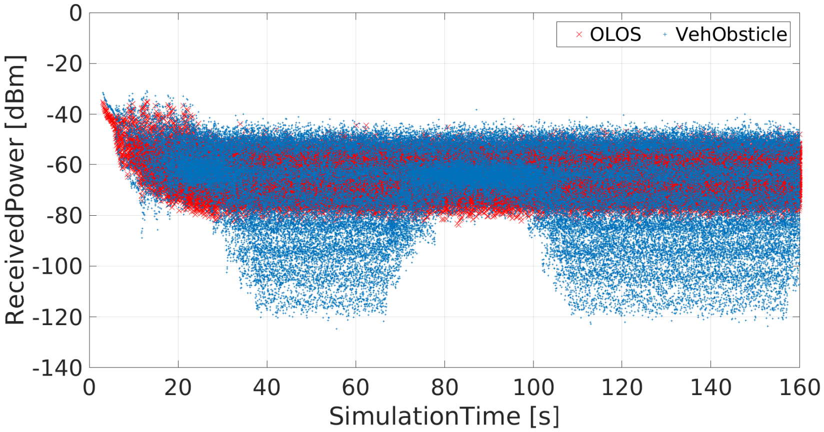


Figure 35: Comparison of Received Power, SingleSlopeOLOS and SingleSlope for LOS + Vehicle Attenuation

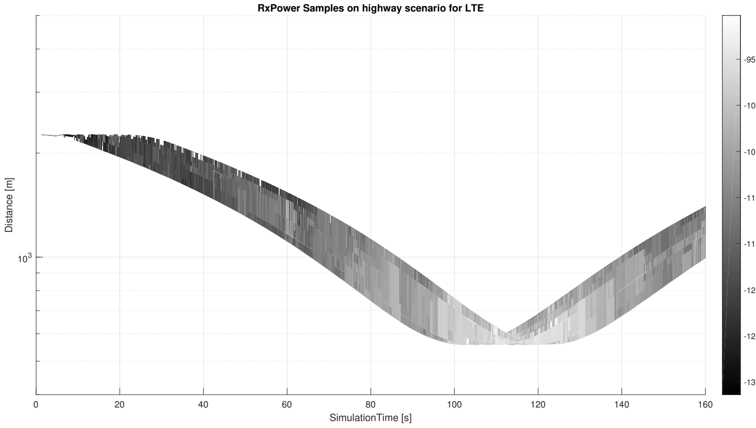


Figure 36: Received Power for LTE based on Distance and the simulation time

7.4.2 Delay

In the highway scenario, we have focused on computing delay since it is a good case for simulating with high a number of vehicles. The delay for different numbers of vehicles and beacons/s has been analysed and investigated. In Fig. 37 we can observe the delay for both LTE and DSRC where a packet of 80 bits has been exchanged between 7 vehicles for 10 Beacons/s.
In the other hand, communication of 8 vehicles is simulated in order to have a rich comparison between the amount of beacons/s. Simulations for 5, 10, 25, 40 and 50 beacons/s have been performed in three cases: 8 vehicles, 19 vehicles and 33 Vehicles in order to see how delay increases for larger amount of vehicles. The analysis is shown in Fig. 38 for DSRC technologies, while in LTE communication delay is reasonable for less than 10 Beacons/s.

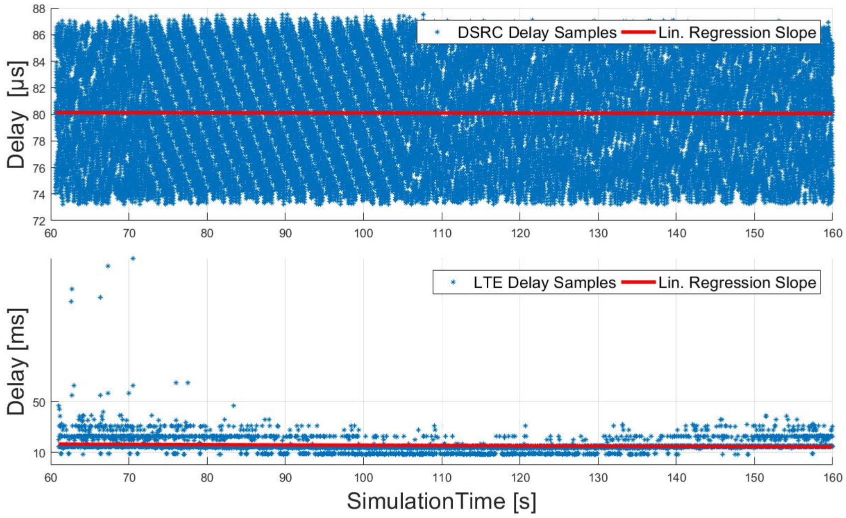


Figure 37: Comparison of Delay in highway for DSRC and LTE. Communication happens through 10 Beacons/s in packet of 80 bits

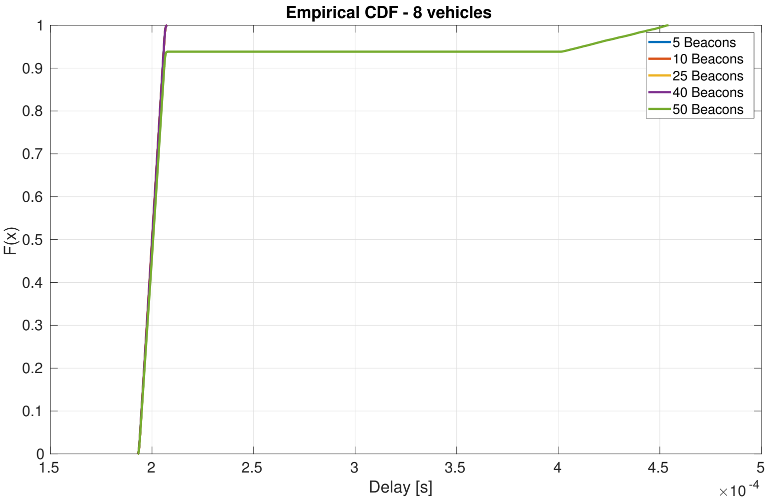


Figure 38

Figure 39: Emperical CDF for simulation of 5,10,25,40 and 50 Beacons/s for 8 Vehicles

7.4.3 Throughput

In the highway scenario besides delay an important performance metric is throughput. Throughput for different number of beacons/s and different number of vehicles has been computed and the analysis is shown in Fig. 40. Computation of throughput for DSRC technologies shows that the throughput is increased with increase on the number of Vehicles or Beacons/second. Increase of the throughput in DSRC happens constantly for DSRC communication. In LTE communication throughput is affected by the delay when the amount of vehicles or number of beacons/s increases.

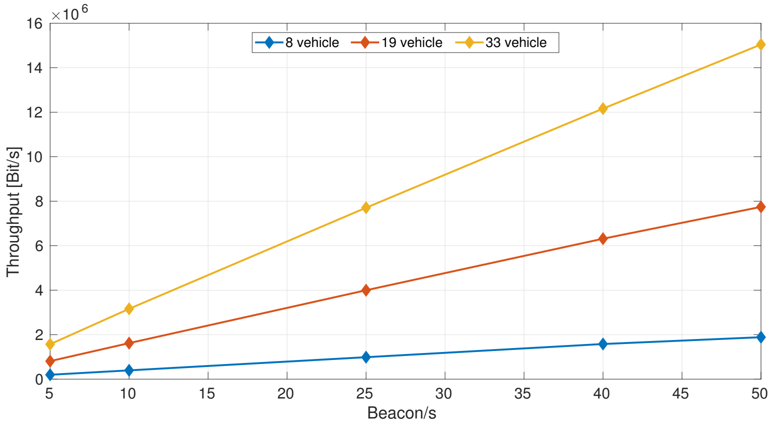


Figure 40: Throughput for DSRC in Highway Scenario

8 Conclusion and Future work

8.1 Conclusion

The advancement of the simulations of vehicular communication for 802.11p and LTE in OMNeT++ has been the crucial point in this thesis. The outcome of this work is a simulation framework with which the user is able to simulate and investigate vehicle communication in different geographical regions such as intersections, roundabouts, and highways.
Completion of the simulation framework made it possible to evaluate and analyze different models. The comparison and evaluation of different models for signal attenuation during simulations brought up the following findings:
In the intersection scenario, the NLOS channel model should be implemented for simulation over the combined models, since the combined models start degrading at distances larger than 100 m compared to the NLOS channel model. Therefore, the simulation output in the intersection has been combined with the Matlab scripts for the NLOS channel model as an alternative solution until this is implemented in the framework itself. The vehicle attenuation model does not have a good estimation if the Truck is the one attenuating the signal. Meanwhile in the highway scenario, single slope channel model for OLOS and the two ray channel model for LOS are used for simulation. The vehicle attenuation model in the highway scenario shows poor behavior since the number of cars is high.
Delay has been investigated by the amount of data in the packet, beacons/s, and number of the vehicles. In communication at 5.9 GHz through DSRC, the delay shows stable behavior and is a very preferable option for safety messages. In LTE, the delay can handle 10 beacons/s for a limited number of vehicles, but it increases if the number of the vehicles starts increasing. However, through LTE we can send huge packet of data compared to DSRC. If we exclude the safety messages through LTE, this would be very suitable for exchanging large amounts of data between the base station and the vehicles. Throughput was investigated and demonstrated for different number of beacons/s and amount of data on the packet.

8.2 Future work

Even though the simulation framework is rich with new features and models, much more research is needed. A crucial improvement would be the update of the LTE stack to the latest releases and adopting the platooning feature into it. Combining models does not seem to be the best approach, therefore a new structure of handling these configurations is necessary. On the other hand, when simulating a large region, the map needs to be divided into specific portions for LOS, OLOS and NLOS in order to use the realistic models, therefore a future contribution can be implementation of an algorithm that gives the ability to the framework for choosing the specific §models itself. As the number of features and models is going to increase more and more for handling these features, machine learning techniques should come to use. In this way the framework will have the ability to decide and learn based on the simulations of different geographical regions.

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