RESOURCE SELECTION FOR CELLULAR V2X AND SIMULATION

(KARA TAŞITLARININ DİĞER YOL NESNELERİ İLE HÜCRESEL HABERLEŞME TEKNOLOJİSİNDE KAYNAK SEÇİMİ VE BENZETİMİ)

by

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ABSTRACT

Vehicular Ad-Hoc Networks is an emerging technology and research area since it promises fast and lossless communication among vehicular nodes. Vehicular to Everything communication targets data sharing between vulnerable road users and cars with mobile network assistance soon. Despite the nature of vehicular mobility and density, V2X requires transmitting massive data over a long range and being lossless. LTE is the most promising infrastructure for cellular V2X messaging, but it is still a developing technology requiring more research. To do so, a simulator environment is a fundamental need. In this thesis study, the literature review is conducted to elaborate on the LTE-V2X characteristics and performance evaluations in simulation environments. Moreover, a customized network simulator coupled with a road simulator is built to enable scalable simulation of various traffic scenarios. A set of physical channel configuration parameters is evaluated to maximize the performance of a fast and lossless ad-hoc communication in road traffic. Performance related parameters are listed and explained in the proposed system scheme. Resource selection techniques of C-V2X are reviewed and discussed.

Our evaluation and test study illustrates that the resource selection algorithm plays a crucial role according to the calculated packet reception rates. Additionally, besides the prior public simulation studies, which conducted to seek the performance of C-V2X, are utilized to develop an NS-3 based open source C-V2X simulation environment with the geo-based resource selection algorithm implementation as a contribution along with comparative simulation studies. The proposed simulation environment introduces scalable and configurable system level and link level simulations in LTE vehicular networks.

Keywords : Vehicular Communication, C-V2X, LTE, Vehicular Network Simulation

ÖZET

Uçtan uca araçsal ağlar, araç ve diğer yol nesne düğümleri arasında hızlı ve kayıpsız haberleşme vaadiyle birlikte gelişen bir teknoloji ve araştırma alanı olmuştur. Önümüzdeki birkaç sene içinde, araç trafiğinin içinde var olan her nesne bu haberleşme yapısına katılma durumundadır. Bu tümleşik haberleşme ortamına literatürde “Kara Taşıtlarının ve Diğer Yol Nesnelerinin Haberleşmesi” (V2X) tanımlaması yapılmıştır. Yol nesnelerinin tamamını içeren bir mobil haberleşme ağı yüksek miktarda veriyi geniş bir alanda ve dirençli bir yapıda kullanmayı gerektirmektedir. Bu zorlu tanımı karşılama noktasında LTE ağları öne çıkmaktadır ancak hala geliştirmeye açık söz konusu bir teknolojidir. Bu tez çalışmasında C-V2X uygulamalarının LTE ağlarındaki benzetimi ortamları, sistem tasarımları, haberleşme karakteristikleri ve performans çıktıları hakkında literatür taraması yapılmıştır. Bu çalışmalar temel başvuru noktası alınarak yeni bir benzetim ortamı kurgulanmıştır. Benzetim ortamı üzerinde haberleşme fiziksel katmanına girdi olan parametrelerle sistem performans çıktılarına yönelik çalışmalar, kaynak seçimine yönelik coğrafi bazlı seçim algoritması uygulamaları ve bu çalışmaların farklı yol tiplerine uygulanması çalışmaları yürütülmüştür. Ayrıca, C-V2X standart incelemeleri, bu teknolojiyi destekleyen simülasyon ortamlarının arasından seçilen simülasyon ortamının özelliklerini ve bu ortamda ettiğimiz karşılaştırmalı sonuçlar paylaşılmıştır.

Anahtar Kelimeler : Araçlar Arası Haberleşme, C-V2X, LTE, Araçsal Ağlar Simulasyonu

LIST OF SYMBOLS

V2X	Vehicular to Everything
VANET	Vehicular Ad-Hoc Network
V2V	Vehicle to Vehicle
V2I	Vehicle to Infrastructure
V2P	Vehicle to Pedestrian
C-V2X	Cellular Vehicle to Everything
DSRC	Dedicated Short Range Communication
WAVE	Wireless Access in Vehicular Environments
ITS	Intelligent Transportation Systems
DENM	Decentralized Environmental Notification Message
CAM	Cooperative Awareness Message
SUMO	Simulation of Urban Mobility
LTE	Long Term Evolution
LTE-V	Long Term Evolution - Vehicle
3GPP	The Third Generation Partnership Project
ETSI	European Telecommunication Standard Institute
CSMA/CA	Carrier Sense Multiple Access with Collision Avoidance
MAC	Medium Access Control
E-UTRAN	Evolved Terrestrial Radio Access Network
UE	User Equipment
eNB	Evolved NodeB
PGW	Packet Gateway
SGW	Service Gateway
PSSCH	Physical Sidelink Shared Channel
PSCCH	Physical Sidelink Control Channel
PRR	Packet Reception Rate
SNIR	Signal to Interference plus Noise Ratio
BLER	Block Error Rate
RSSI	Receive Strength Signal Indicator
RSRP	Reference Signal Received Power
RSRQ	Reference Signal Received Quality

1 INTRODUCTION

Vehicular Ad-Hoc Network (VANET) is a developing technology area in recent years regarding digital technology improvement and industry trends. In the road traffic environment, every object will be communicated in the next few years. Active safety and autonomous driving technologies have emerged, and in line-of-sight and non-line-of-sight road areas, information sharing between vehicles, roadside units, pedestrians, cyclists, and information services named Vehicle to Everything (V2X) communications have been presented recently. Communication of everything in road traffic requires handling massive data over long range areas and needs high robustness. To overcome with requirements of communication technologies on Long-Term Evolution (LTE) networks are began to discuss for further deployments of V2X. Former vehicle communication protocols have been performed with an underlying IEEE 802.11p physical layer, which is an implementation of wireless access in vehicular environment (WAVE) with an amendment of 802.11 Wi-Fi. Developing and widely deployed LTE networks become a promising technology for V2X communication assuring end-to-end latency and packet delivery robustness. The integration of the V2X in LTE networks is called Cellular V2X (C-V2X) or LTE-V2X. Earlier vehicular communication technologies introduce Cooperative Awareness Messages (CAM) and Decentralized Environmental Notification Messages (DENM) messaging types for safety or information applications but in addition to these messages, video and audio data assisted messages have been recently used through deployment of advanced functionalities of V2X. This usage causes massive data transport rates, which may not be supported by existing IEEE 802.11p systems. At the current stage, C-V2X communication technologies are being developed on the LTE networks. In meantime, the C-V2X communication performance on the LTE networks is being evaluated and tested along with communication capabilities and quality services. Feasibility tests and developments are conducted by industry and academia with collaboration, and test scenarios run both in real road cases and in computer simulation environments.

Like 802.11p, LTE has a specific vehicular communication extension, which is the LTE-Vehicle (LTE-V). The 3rd Generation Partnership Project (3GPP) has a leading role in the development of The Mobile Broadband Standard LTE. LTE support for V2X services was initially included in 3GPP releases with Release 14 (3GPP, 2017). LTE-V2X or LTE-V and

5G LTE requirements are presented in a Technical Report with introducing of expectations on performance outcomes of C-V2X, specialized direct communication interface PC5. In 3GPP Release 15 (ETSI, 2018), possible improvements have been discussed such as carrier aggregation, reduction of the maximum time between arrival and start, and shared resource between Mode 3 and Mode 4 to reach real life scenarios performance expectations. During the thesis study, all new releases and academic contributions regularly reviewed to understand new developments and analyze possible bottlenecks of this technology.

Besides prototypes and feasibility reports from the industry, there are researches about V2X on LTE in standard organizations and academic researches. Especially after Release 14, academic and industrial research projects and publications about C-V2X have been increased. Because of newly developed communication infrastructures and strict performance requirements, simulation environment need is another issue. Simulation has an important role in this technology because it is in the early development stages and vehicular based real life tests are costly. But except for several research studies, there were no open source system level simulation implementations according to the 3GPP C-V2X specifications. Also, in many simulation studies' results could not meet with theoretical communication performances yet. Several options for network, vehicular movement simulators, and integrated VANET simulators exist. In this study, a SUMO integrated NS3 simulation environment is utilized with the help of previous examples to evaluate and test several vehicle communication scenarios. To create road traffic simulation, SUMO is a validated tool. It generates movement models with various road networks, different numbers of vehicles, and speed variations. SUMO also has vehicle movement output files that can be used in network simulators. On the network simulator part, NS-3 is chosen due to its availability of open source code on all network layers. NS-3 has an academic and professional support community.

This thesis study aims to research and simulate vehicle to everything communication on LTE networks extensively and propose a flexible simulation environment with resource allocation algorithm options. Also, it includes technical standards and literature reviews, simulator availability in V2X on LTE, and latest simulation results, resource allocation algorithms, and future work for C-V2X researches. In Section 4, the C-V2X infrastructure and the details of LTE physical layer for ad-hoc communication implementations are elaborated. In Section 5, simulation environments are discussed, and the system level simulator structure is explained. Besides the available ready to use simulators, modifications have been needed to perform to adapt new C-V2X requirements and resource allocation algorithms. Since the characteristics of the simulation software environment are so crucial, in Section 5. 4 modified simulation environment from an open-source code is presented with a geo-based scheduling resource selection algorithm proposed to manage radio resources. The reference simulation environments and publications are described in that section. In Section 6, parameter optimizations for performance maximization on different road topologies are summarized. Finally, findings and future works for research possibilities are discussed in Section 7.

2 LITERATURE REVIEW

Thesis study includes several parts to survey for pre-conducted literature. It can be divided into four subsections vehicular communication technologies, vehicular networking simulations, current LTE developments for vehicular networks, and LTE vehicular communication simulations. LTE vehicular communication simulations can also be used for performance result comparisons with thesis study results.

A comprehensive study about vehicular communication on different infrastructures and LTE on 5G advantages over 802.11p is presented in (Araniti et al., 2013). A system level analysis and LTE, 802.11p comparison in terms of packet drop rates over distance can be found in (Roux et al., 2019). In (Sattiraju et al., 2020) link level analysis, and in (Karoui et al., 2020) end to end delay and SINR based quality of service is elaborated for C-V2X. These four studies are the fundamental pivot point for this theses' performance evaluations, while the last three research are up to date publications. For the vehicle to pedestrian use cases, (Aslani et al., 2020) can be evaluated as a solid reference with its comprehensive physical layer theoretical explanations, and also resource selection viewpoint is important reference for this study. In (Chen et al., 2016) a systematic and integrated V2X solution based on a time division LTE is proposed. While it is released in 2016, only LTE Mode 1 and Mode 2 are considered. Their work includes early results about LTE packet reception rates regarding to transmit power and distance. Another study of Chen (Chen et al., 2017) is a survey about LTE based V2X. A set of example test parameters are extracted from 3GPP Release 14 requirements for speed, latency/reliability, message size and message generation period. Also, critical element of C-V2X semi-persistent scheduling (SPS) is explained in detail.

Molina-Masegosa's A New 5G Technology for Short Range Vehicle to Everything Communications (Molina-Masegosa and Gozalvez, 2017) work is a fundamental reference in literature to understand the physical layer of this technology. It has nearly 350 citations, while it explains new physical channel modeling for LTE V2X in details and gives the very first C-V2X performance evaluations. Through this research, LTE based reviews were conducted.

As the main proposal of this thesis is a simulation environment for vehicular communications, it has been reviewed. A comprehensive reference is found in (Shafiee et al., 2011) as a survey of simulation of vehicular networks. Although it gives clear and wide approaches about simulation ; (Raj et al., 2014),(Liu et al., 2016) have been reviewed for network simulation and road simulations couplings. In the early stages of this research LTE, 5G and mm-Wave network simulator availability have been conducted, and in (Mezzavilla et al., 2018) NS3 LENA based discussion, model explanation and simulations analyses used to understand many LTE integration on NS3 fundamentals. In (Bonjorn et al., 2018), Release 15 based LTE V2X simulations and resource selection implementation is given with clear definitions and details.

One of the other popular research topic is comparing IEEE 802.11p and LTE V2X performances in different use case scenarios. In study (Jacob et al., 2019) C-V2X and IEEE 802. 11p comparison performed with a highway scenario. C-V2X is tested in NIST LTE-D2D NS-3 (Rouil et al., 2016) simulation environment with customized V2V configurations. Another comparison of two technologies study (Shi et al., 2019) is performed in a real world experiment with two cars in an experimental area in National Intelligent Connected Vehicle (Shanghai) Pilot Zone in Jiading District, Shanghai. This study does not cover any comparison between IEEE 802.11p and LTE V2X, but reviewing resources about initial studies are valuable to determine methods and technical expectations. Another physical test scenario study (Fan et al., 2020) published in 2020, and it is one of earliest real world examples of C-V2X examples in literature. Their submitted results are important to validate simulation results in the application.

As the LTE and related C-V2X technologies are not deployed and still under development, up to date researches are valuable resources to improve for further studies. Some examples of recently published are reviewed for checking the latest contributions. In (Chen et al., 2020), a comprehensive C-V2X vision assessment was performed with deployment cases. In (Saifuddin et al., 2020), performance analysis of C-V2X regarding to the transmit power and communication distances. (Lagen et al., 2020) has a detailed physical layer explanation about 5G New Radio implementation in NS-3, and this study is valuable to implement new features in simulator environments.

3 VEHICULAR AD-HOC NETWORKS

With the need for vehicle based communication technologies, vehicle specific ad-hoc network is introduced as Vehicular Ad-Hoc Networks (VANET). VANET is a specialized mobile ad-hoc network. Ad-hoc networking is an important issue in vehicular communication as mobile networks because of vehicles' high mobility characteristics. Frequent change of communicating pairs due to rapid position change is the main difficulty both for applications and protocol implementations. Ad-hoc networks are used for temporarily defined local area networks for special purpose usage. Generally, broadcast message applications run on the application server services. One of the biggest advantages of ad-hoc networks is performance issues. To overcome these issues and with the communication technology developments, ad-hoc and VANETs infrastructure deployments are evolving. Several technologies have been developed and deployed as test usage up to now. There are several communication definitions in vehicular networks. These are Dedicated Short-Range Communications (DSRC), Wireless Access in Vehicular Environments (WAVE), and lastly, Cellular V2X (C-V2X).

As a term of the vehicular network does obtain all communication objects in the network with their names. Today vehicular networking includes pedestrians, bicycles, traffic lights, other roadside units, and many different road objects besides vehicles. The common name is the vehicle to everything (V2X) for all of the communication types. Vehicle to infrastructure defines communication between vehicles and road infrastructures such as traffic lights, emergency communication units, lane markings, and road RFID devices, traffic signs, road surveillance systems. All these systems are developed for intelligent transportation systems (ITS), and their interaction defines cooperative intelligent transportation systems (C-ITS). C-V2X is the most important underlying component in C-ITS part for reliability and safety of each road traffic participants.

3.1 DSRC, 802.11p, WAVE

Dedicated Short-Range Communication (DSRC) is a protocol to enhance road safety applications as an over-the-air communication technology. DSRC is based on IEEE 802.11p (IEEE, 2010) which is a standard of the Institute of Electrical and Electronics Engineers and an extension of 802.11 standards for wireless local area networks. IEEE 802.11p is generally used as a term instead of DSRC. It defines medium access layer and physical layer specifications of Wireless Access in Vehicular Environment (WAVE). It is allocated at 75 MHz of 5. 9 GHz band to use in intelligent transportation systems only as declared US Federal Communication Commissions (Commission, 1999). It is also named ITS-G5 in Europe and allocated at 30 MHz of 5. 9 GHz band (ETSI, 2010). Besides PHY and MAC layer, WAVE has a specified protocol that WAVE Short Message Protocol (WSMP) in the data plane. The management plane has management entities for transport MAC and PHY layers and security service entity.

DSRC enables direct vehicle to vehicle and vehicle to infrastructure messaging without cellular or any other wireless network coverage. DSRC deployed in autonomous driving assistance systems (ADAS) mainly none line of side applications. One of the most recent vehicular networking studies with 802.11p review is (Arena et al., 2020), and includes a comparison of C-V2X and IEEE 802.11p. In real life scenarios, DSRC has been deployed widely neither by industrial nor governmental projects. With the developing LTE technologies, DSRC may be only used as a supplementary protocol for some ADAS applications in the future.

3.2 Message Protocol for Vehicular Networks

A common message protocol is important for every technology. LTE V2X has not been associated with a standardized message type yet, but Cooperative Awareness Message (CAM) and Decentralized Environmental Notification Message (DENM) protocols are defined by ETSI are existing protocol for vehicular communications. DSRC applications have been used that message packets. CAM messages are used as a periodic heartbeat message. On the other hand, DENM messages are used for avoidance purposes. The details for these two message types are clearly explained and obtained in vehicle to infrastructure applications in (Santa et al., 2013).

A research article (Kim and Lee, 2017) specifies an example simulation with DENM messages on LTE networks which is an important reference to the message protocol implementation for LTE networks. An example of general purpose vehicular messaging packet type can be defined as shown in Fig. 3.1.

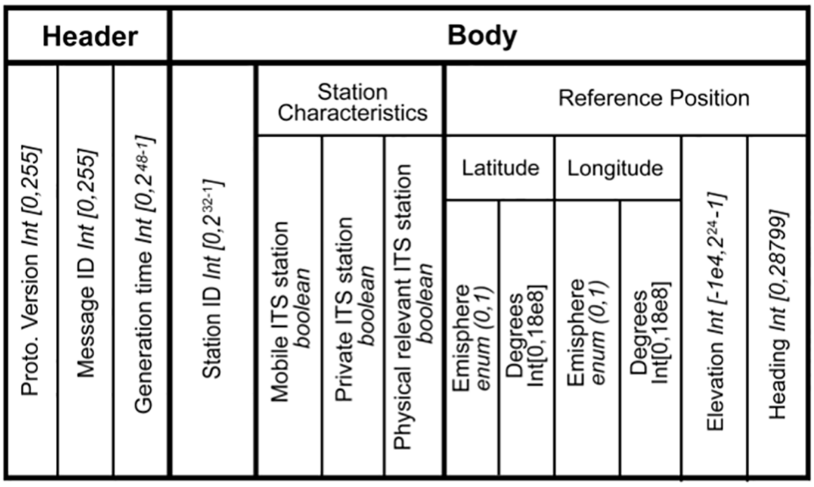

FIGURE 3.1 – Vehicular Communication Message Type Architecture

4 LTE V2X

Long-Term Evaluation (LTE) is known as a standard wireless communication technology for up-to-date mobile devices and other cutting edge connected devices. The LTE standard development was conducted by The 3rd Generation Partnership Project (3GPP) group of seven standard development organizations. These organizations are ARIB, ATIS, CCSA, ETSI, TSDSI, TTA, TTC (3GPP, n.d.). Based on 3GPP Release 8 in December 2008, LTE has been introduced. The motivation for the LTE is continuity of competitiveness of the 3G systems for the future with high data rates and quality of service enhancement, packet switch optimized system, continued demand for cost reduction, low complexity, and avoiding unnecessary fragmentation of technologies for paired and unpaired band operation (ETSI, 2016). 3GPP has been released eight more releases which include enhancements and advancement in LTE technologies up to now. The release history can be seen in Appendix 1. All of the details of sub-elements of LTE have been described in Technical Specifications documents TR 36.885 (3GPP, 2017). LTE related technical specifications (TS) or technical reports (TR) documents are generally written by the European Telecommunication Standards Institute (ETSI). For different regions, some terms are changed by regional standards authorities.

LTE is named also Evolved Universal Terrestrial Access Network (E-UTRAN). As LTE aims for internet protocol (IP) based communications, it has a different layer for that and named as Evolved Packet System/Core (EPC). E-UTRAN is the access point to EPC. LTE Access Network consists of the base station named evolve NodeB (eNB). eNBs can intercommunicate over X2 interface, and communicate with the core network - EPC - via S1 interface. The general architecture of LTE is shown in Fig. 4.1. Some of the fundamental

sub-elements of LTE architecture are defined in related specifications.

— TS 36.211 Evolved Universal Terrestrial Radio Access (E-UTRA) ; Physical channels and modulation

— TS 36.212 Evolved Universal Terrestrial Radio Access (E-UTRA) ; Multiplexing and channel coding

— TS 36.213 Evolved Universal Terrestrial Radio Access (E-UTRA) ; Physical layer procedures

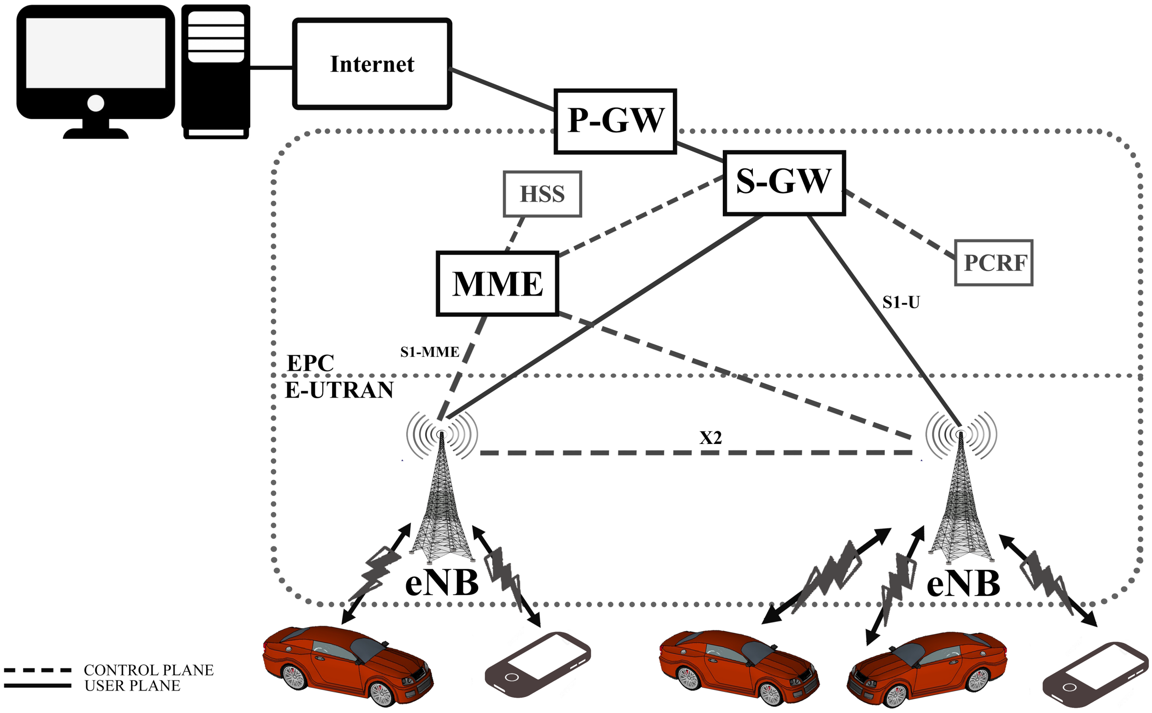

FIGURE 4.1 – LTE Networks Architecture

- TS 36.300 Evolved Universal Terrestrial Radio Access (E-UTRA) and Evolved Universal Terrestrial Radio Access Network
- TS 36.321 Evolved Universal Terrestrial Radio Access (E-UTRA) ; Medium Access Control (MAC) protocol specification
- TS 36.331 Evolved Universal Terrestrial Radio Access (E-UTRA) ; Radio Resource Control (RRC) ; Protocol specification
- TS 36.413 Evolved Universal Terrestrial Radio Access Network (E-UTRAN) ; S1 Application Protocol (S1AP)
- TS 36.423 Evolved Universal Terrestrial Radio Access Network (E-UTRAN) ; X2 Application Protocol (X2AP)

These technical specifications are the main reference points for simulation or deployment applications. Different detailed protocol layers, use cases, quality of service topics are discussed in these documents and such documents should be reviewed in the early stages of research or development studies. Theoretical expectation from LTE is communicating at high data rates up to 300 Mbps downlink and 75 Mbps uplink. These rates are defined with usage of 4x4 Multiple-Input Multiple-Output (MIMO) antenna for downlink and 1x2 MIMO antenna for uplink at 20 MHz bandwidth. To reach these requirements orthogonal frequency division multiplex (OFDM) was implemented for the physical (PHY) layer. Besides the OFDM signaling, MIMO antenna usage increases spatial multiplexing and signal robustness with space frequency / time coding. In 3GPP releases, a channel quality indicator (CQI) list is defined. In that indexing table, modulation and code rates are defined. With modulation and coding scheme throughput, latency, transmit distance, and signal robustness can be affected in a variety of ways.

Since the current V2X applications require high bandwidth and fast data rates because of real-time and critical operation features of applications, IEEE 802.11p may inadequate for future developments. Thus, LTE is the lead infrastructure for this technology with its larger bandwidth to support many endpoints at the same time in a reliable environment with high quality of service. By Release V14.0.0 in June 2017, V2X based use cases were introduced which includes vehicular communication in LTE specific topics. The main contribution of LTE-V2X is that it has different operation scenarios that are with or without LTE network coverage. Carriers are both dedicated to LTE-based V2X services or carriers are licensed spectrum and also used for standard operations.

4.1 LTE-V2X Access Network

Access network of LTE is about the communication of individual endpoints User Equipment (UE) and network access point evolved NodeB (eNB). UEs can communicate with eNBs via cellular inteface uU. In this network, LTE has a customized interface which is PC5 to support device-to-device communications. PC5 direct communication link is introduced in Release 12. But it is specific to mobile end-to-end communications. In release 14, two new communication modes were introduced. These modes are mode 3 and mode 4. Customization is related to physical layer specifications. In release 15, LTE-V2X evolution on these modes to support fifth-generation (5G) V2X communications and autonomous vehicles' applications. Mode 3 and Mode 4 support direct V2V communications but have a different implementation on source allocation. Mode 3 supports under network coverage and Mode 4 is for non-covered areas. Mode 4 is considered as an alternative of 802.11p or other DSRC communications as shown in Fig. 4.3.

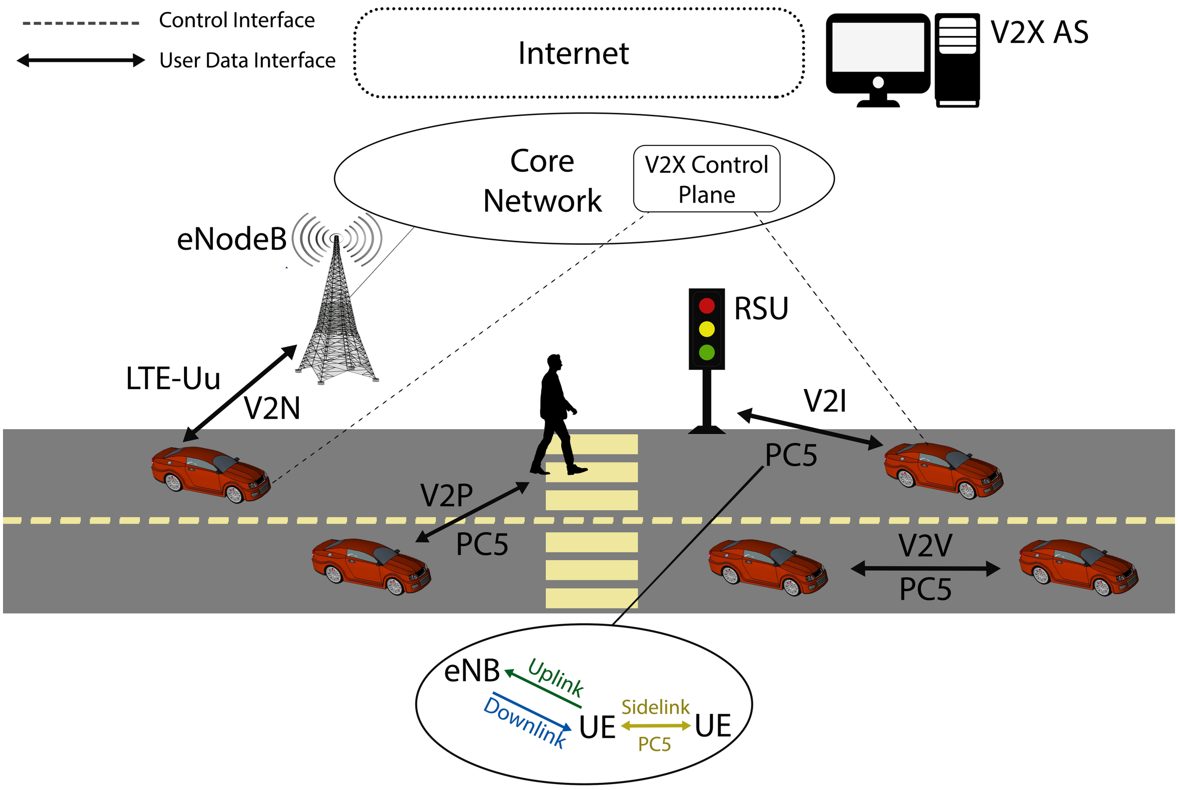

FIGURE 4.2 – LTE-V2X Networks Architecture

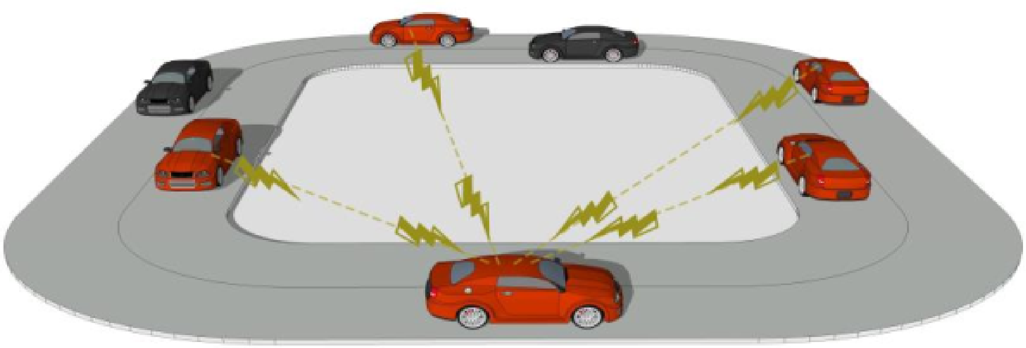

FIGURE 4.3 – Out of Coverage Communication (Mode 4)

In under LTE signal coverage network decides channel configurations, on the other hand for out-of coverage scenarios carrier frequency, subchannel structure and synchronization references are decided by UEs itself.

LTE-V uses single-carrier frequency-division multiple access. Depends on the regulations, communication channel is divided into subframes, resource blocks, and sub-channels.

Subframes have a 1 millisecond long as a transmission time interval. Resource blocks (RBs) are the smallest unit of frequency resources for each user, subchannel is a group of RB in the same subframe. The number of RBs could be changing for every subchannel. In LTE-V2X model, the data is packed into transport blocks (TBs) while its information is gathered in sidelink control information (SCI) which both are transferred through physical sidelink shared channel (PSSCH) and physical sidelink control channel (PSCCH) respectively. Two different subchannel methods exist as the first one is the adjacent PSCCH + PSSCH in which TB and SCI are sent consequently and the first two RBs contain SCI information, while the other one is the nonadjacent PSCCH + PSSCH that contain SCI and TB pools. These elements are illustrated in Fig. 4.4. In terms of the application parameters, they may differ

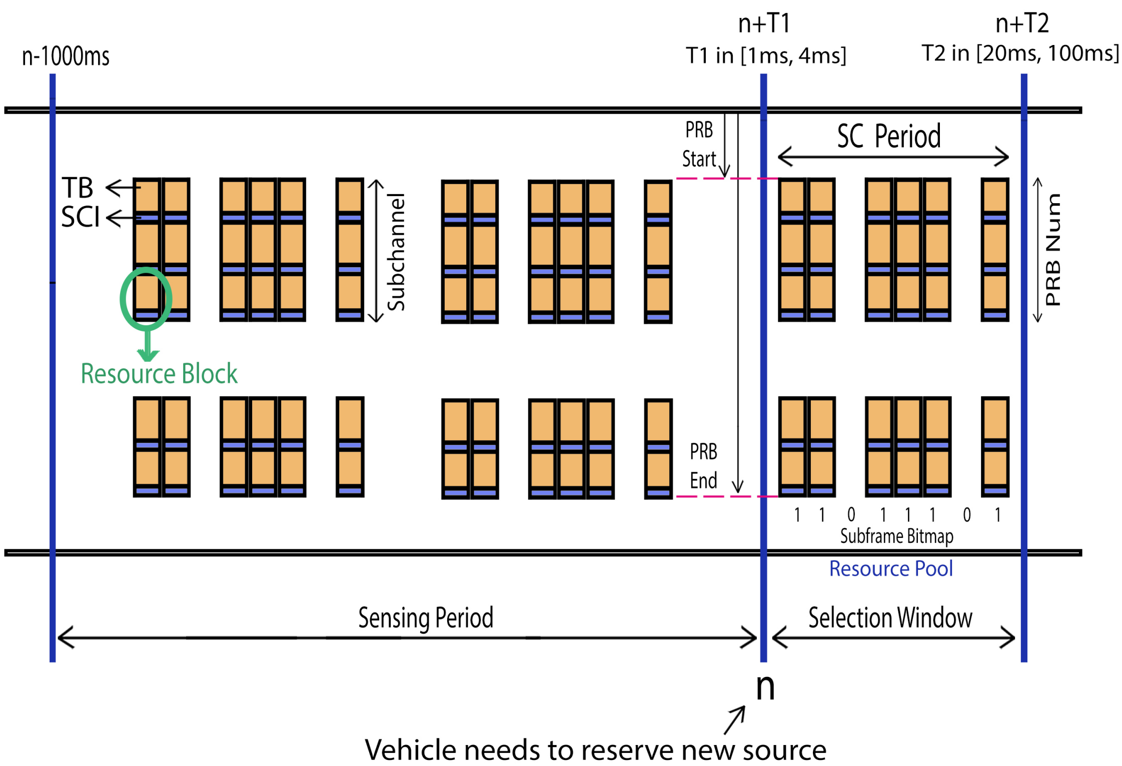

FIGURE 4.4 – LTE Physical Cannel Structure

according to the vehicle nodes' coverage states and running modes. For example, in mode 4 for V2V communication, vehicle nodes have an autonomous selection of their resource parameters when in coverage or not. For V2X communication if cellular coverage exists, then the network decides the configuration of V2X parameters. However, if vehicles are not under cellular coverage, pre-configured parameters are applied. For mode 3, cellular coverage is a must, and base station or evolved NodeB (eNB) is responsible for configuration management.

The releases of 3GPP do not dedicate a congestion control algorithm for applications however, it defines metrics and offered mechanisms like channel busy ratio (CBR) and occupancy ratio (CR) (3GPP, 2017). Packet dropping, number of transmissions, modulation and coding schemes (MCS), reservation of subchannels, and transmission power related to CBR and CR are parameters that affect the overall system performance. These parameters should be carefully utilized and test during the design and simulation steps.

In LTE V2X, it is expected that network infrastructure could handle transmission up to 50 packets per second and maximum 10 milliseconds latency with 99.99% reliability (ETSI, 2017). In 3GPP Release 15, some improvements are discussed such as carrier aggregation, reduction of the maximum time between arrival and start, transmit diversity, and shared resources between Mode3 and Mode 4 to fulfill expectations.

4.2 Core Network

The core network consists of Packet Gateway (PGW), Service Gateway (SGW), and Mobility Management Engine (MME). Understanding of these network specifications is important to apply modifications for vehicular network related messaging. PGW is the entry point of data traffic from the internet to UEs, while also connected to the other 3GPP services and non-3GPP services. SGW lies between PGWs and eNodeBs and responsible for routing and forwarding user data packets. The key element in LTE networks is MME which is responsible for inter-core network node signaling for mobility between 3GPP access networks, UE control, and paging procedure including re-transmission, UE accessibility process, mapping of UE location PGW and SGW selection, bearer management, handover management, authentication, and authorization.

4.3 Radio Resource Selection

4.3.1 Semi Persistent Scheduling

Radio resource selection is a technical detail that significantly affects the performance and system stability in LTE networks. Various algorithms in this area are available in the literature. Although 3GPP does not make a mandatory routing in this area, the sensing-based semi-persistent scheduling algorithm is defined shown in Fig. 4.5.

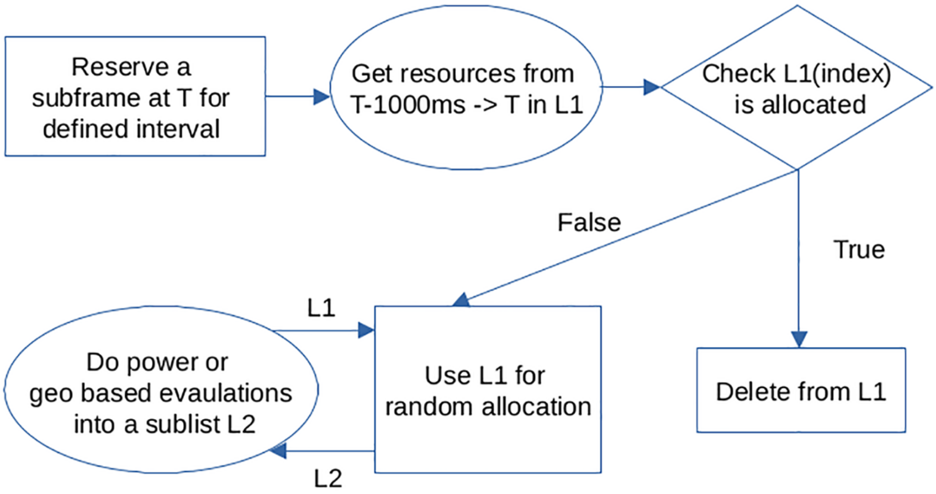

FIGURE 4.5 – SPS Algorithm Flow

4.3.2 Resource Pool Selection

Another resource selection in applications is resource pool organizing. This is not a defined specification or definition. It is an implementation of a logical partition of resources besides time and frequency division. It can be visualize as shown in Fig. 4.6.

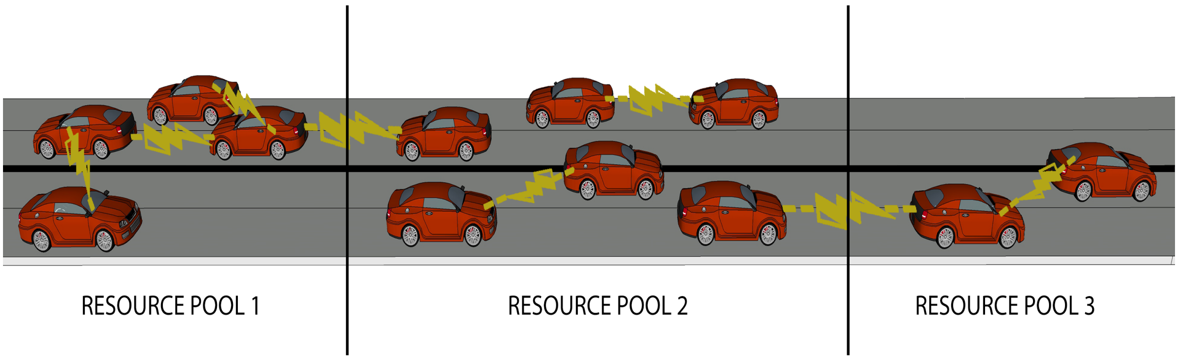

FIGURE 4.6 – Resource Pool Selection

4.3.3 Geo-based Scheduling

When active nodes in communication have mobility, their locations and relative positions should be count. Propagation of their signal, handover states, and congestion on scheduled resources can affect their mobility characteristics.

One of the subsets of mobility is the position of that node. Geographical position data can be used with many different algorithms. In LTE, packet collision on same air media resource are one of the challenged problem in congested networks. Resource selection according to the geographical position named as geo-based scheduling in literature and one of the example is (Molina-Masegosa et al., 2019). Masegosa states that geo-based scheduling used to resolve hidden terminal challenges in vehicular networks.

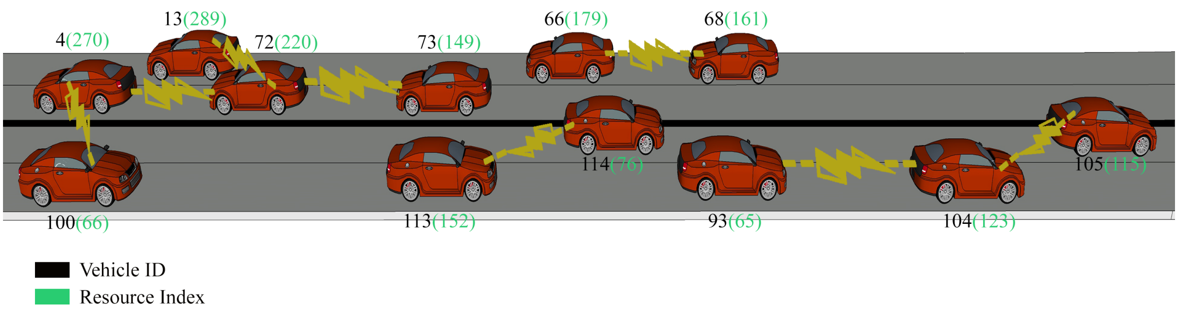

FIGURE 4.7 – Geo Based Resource Scheduling

5 SIMULATION ENVIRONMENT

The simulation environment of vehicular communication needs two fundamental components. The first one is a network simulator, and the other is a traffic simulator, while the capability of integration of these is imperative. Several feasible alternatives exist for both simulations as discussed in (Shafiee et al., 2011). VISSIM and SUMO have been widely used for vehicular mobility simulations in many examples. For network simulation, OMNeT++ and NS-3 have been used and referred by many researchers.

5.1 Road Traffic Simulator

Growing both urban and large-scale logistic based vehicle traffic (including shipping, air transport, railway, or road transportation) needs to be simulated to optimize their behavior. Traffic simulators are generally used for that purpose. Urban traffic scenarios specifically are studied for smart city planning connected vehicles, autonomous vehicle technologies. Mobile applications, smart cities, or car applications become integrated with real time or prediction of traffic data based traffic simulators. These simulators are the best way to develop new applications, as well as for academic researches, since creating traffic scenarios with real objects and in real environments nearly impossible due to its cost. There are several traffic simulators in the literature. These simulators are, Quadstone paramics, VISSUM , VISSIM , AIMSUN, Matsim, SUMO , Repast, MAINSIM while some of them are free some of them are not.

Traffic simulators are generally categorized by two models which are microscopic and macroscopic. Macroscopic models are related to the flow, speed, and density of the traffic stream and do not use individual vehicles. They are utilized widely to analyze the sub-networks, corridors, grid networks, highways, etc. On the other hand, microscopic simulation models simulate the movement of individual vehicles based on car-following and lane-changing theories. These models are effective in evaluating heavily congested traffic conditions, complex geometric configurations, and system-level impacts of proposed transportation improvements that are beyond the limitations of other tool types. When utilizing vehicular ad-hoc networks (VANET), a microscopic model is a more convenient solution as a traffic generator, because individual network nodes can be defined. Various movement models in a variety of road networks, different number of vehicles along with speed variations can be assigned to each vehicle.

According to the performed literature review, SUMO (Behrisch et al., 2011) is the most suitable traffic simulator for a C-V2X project, since has wide usage in this research area and provides realistic road scenarios. Also it has NS-3 or OMNet++ compatible API called TraCI. Integrating with digital road map data such as OpenStreetMaps is another attractive feature, and real map-based simulations can support road tests. The most important feature of SUMO is to have a trace file output of the simulation which makes it possible to use this output file in a network simulator input. In a VANET project, SUMO trace XML output files can be used as network node movements. Also, dynamic feedback information packets exist about different traffic behavior, route changes, altered speeds or destination points of individual vehicles that can resend the simulation in simulation time. Traffic Control Interface (TraCI) API (Wegener et al., 2008) handles the integration of SUMO and network simulators that two way information flow that makes it possible to route the cars vary speeds and change destination of the car over exchanging network messages. Traffic simulator executes a simulation step then gives feedback of current vehicle positions to network simulator. Then the network simulator continues to the execution of simulation with new vehicle positions. Traffic simulator is one simulation step ahead of the network simulator. Changing speed, route, lane, and destination, and stopping is possible behavior of traffic simulation. Detailed protocol details and data types about TraCI API can be found in work (Wegener et al., 2008). Also, the official website of SUMO has an TraCI API wiki page with its UML diagrams. In this study, dynamic TraCI communication exists between SUMO and network simulator.

5.1.1 SUMO Simulation Configuration Steps

The user should integrate a mobility model with an appropriate trace file format which is generated from the SUMO traffic simulator in this work. SUMO traffic simulation is created by two fundamental files which are "_name.node.xml" and "_name.edg.xml". "_name.nod.xml" that define location of junction points. "_name.edg.xml" includes target and source node IDs. With a netconvert shell command : "»netconvert -n _name.nod.xml -e _name.edge.xml -o _name.net.xml", a route file _name.net.xml is created. Routes are defined by "_name.rou.xml" file. "_name.net.xml" and "_name.rou.xml" are integrated with a configuration file _name.sumo.cfg to simulate created scenario.

Simulation can be traced by different options execution of with different commands as ;

Log file : »sumo -c first.sumo.cfg

GUI : »sumo-gui -c first.sumo.cfg

Trace file : »sumo -c first.sumo.cfg –fcd-output trace.xml

The graphical represantation this configuration flow is shown in Fig. 5.1

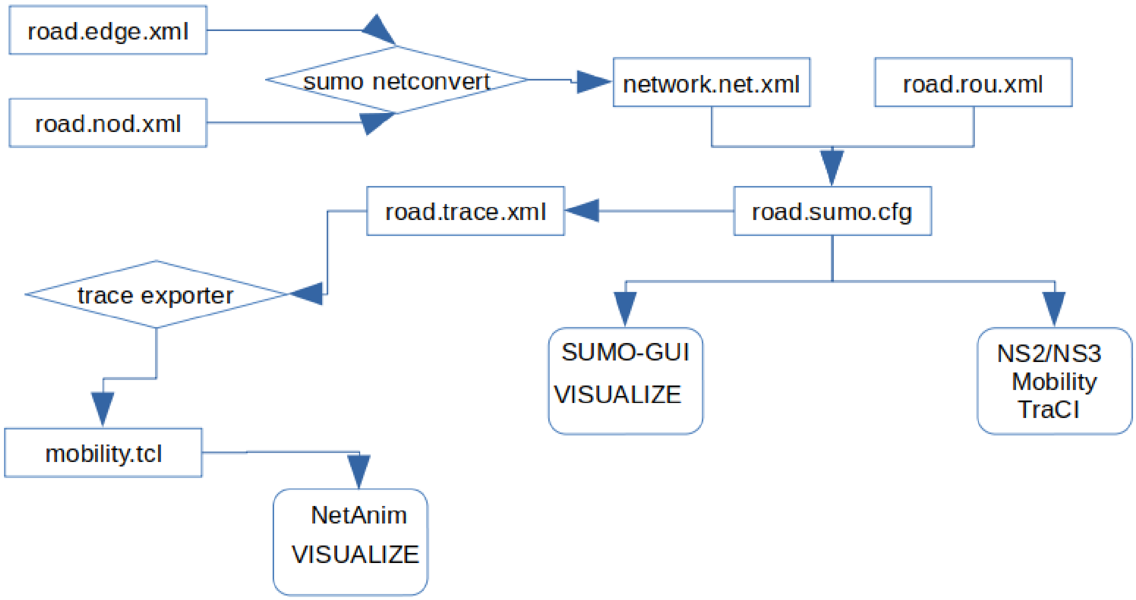

FIGURE 5.1 – SUMO Configuration Flow

Trace file trace.xml can be used within network simulators. The NS-3 network simulator has a mobility helper class for provide network node mobility. A simple network simulation of mobility model can be executed Example command : "./waf –run "ns2-mobility-trace –traceFile = $HOME/vanet/example /ns2mobility.tcl –nodeNum = 150 –duration = 90.0 –logFile = $HOME/vanet/example1 /main-ns2-mob.log"".

The visual demonstration of simulation can be performed by SUMO GUI graphic user interface or NetAnim module of NS-3. SUMO uses sumo.cfg file while the NetAnim needs the simulation animation file declared in the mobility helper class and created as an .xml file after simulation execution completion.

The other tool to create different road topologies is the netedit tool. It is a graphic user interface tool of SUMO. It can be used to create networks from scratch and to modify all aspects of existing topologies. After the creation of road models, vehicle movements are defined with route .xml files in SUMO. Route files can be used to declare vehicle and their types (car, bus, truck) with unique identification numbers, acceleration/deceleration values, physical lengths, departure speeds and lanes, repetition characteristics (begin time, end time, vehicles per hours, the probability for an emitting vehicle in each second).

5.2 Network Simulator

Network simulation is simply software that predicts a computer network's behavior under different circumstances. Eventually, network simulation becomes more important because of the rapid development of the internet and mobile communication technologies. Computers, phones, homes, cars communicated with each other or different type of node, and now everything become a part of this connectivity. The incredible amount of data traffic over different infrastructures makes the computer networks complicated. A computer network design needs to be modeled with different features. Therefore simulators come with different end and host devices, link layers, applications, wireless LANs, mobile ad-hoc networks, wireless sensor networks, vehicular ad-hoc networks, cognitive radio networks, LTE/ LTE-5G, internet of things modules.

A network simulator may come with both command line interface and graphical user interface generally. There is lots of network simulator. When considering VANET researches, some simulator has common usage in literature in this area. These simulators are OPNET, OMNET++, NS-2, and NS-3. To perform a C-V2X study, a network simulator should support LTE infrastructure modeling and able to use with SUMO trace file outputs. OMNET++ based VeinsLTE and NS-3 are the top two simulators that have appropriate features. NS-3 is more convenient in academic researches with its tested and validated modules and its widely supported open-source code architecture. In this study, the NS-3 network simulator is used due to its LTE module availability (NSNAM, 2012) and solid references about simulation VANET in NS-3 (Raj et al., 2014), (Liu et al., 2016).

NS-3 is a discrete event simulator in which time flows in discrete steps from event to event. Functions schedule events with specific simulation times. The simulation ends at a specific time or end of the event. NS-3 is written in C++ and it is an open source project. Also, it has python modules that perform integration, configuration, running, and visualization. It is compatible with its predecessor NS-2. For example, the mobility module is exactly inherited from NS-2. NS-3 has different categorized modules such as devices (bridge, spectrum, LTE, WiFi, WiMax, mesh point-to-point), protocols (AODV, DSDV, OLSR, click, openflow), utils (visualize, netanim, flow-monitor). The NS-3 LTE module which includes two model LTE and EPC. LTE model has the LTE radio protocol stack (RRC, PDCP, RLC, MAC, and PHY). EPC model includes core network interfaces, protocols, and entities. These entities and protocols reside in SGW, PGW, and MME and partially in eNB nodes.

As mentioned in Section 4, vehicular network implementations on the LTE network have some differences from standard LTE. At the time of writing this thesis, the official release of NS-3 does not have LTE device-to-device communication. The NS-3 Public Safety Communications distribution (NS3-PSC), (Rouil et al., 2016) which has a PC5 device-to-device communication interface implementation, is developed corresponding to the case scenarios of 3GPP Release 12 for public safety communication. The PC5 interface implementation is a must to simulate vehicular networks and NS3-PSC gives the availability of PC5 with and without cellular coverage modes, and there is no other open source implementation for a PC5 interface for NS-3. In (Rouil et al., 2016), "LTE radio protocol stack architecture for the UE on the data plane" and "New PHY and channel model architecture for the UE" is given as software definition tables.

5.3 LTE simulation with NS-3 PSC 2.0

The first step of the simulation is testing the NS-3 LTE module with mobility module integration. The NS-3 does not have a ready to use an example of LTE mobility; however, it is simple to integrate. In our initial LTE simulation, two implementations have been tested. The first one includes only vehicular mobility on the access network and supports up to 30 vehicles with default NS-3 LTE simulation configuration parameters. In our scenario, simulation creates 1 eNodeB and n (n<=30) uE. Then trace file is included and its mobility installed to uE. In this scenario eNodeB located constant 0,0 position. Created uEs and eNodeB are defined as LTE devices. The data radio bearer is activated as LTE specified. Then simulation starts and loggers gathered simulation info. The program main flow is given in Fig. 5.2. This simulation has a media access controller (MAC), radio link controller (RLC) physical layer transmitter/receiver, and signal to interference plus noise ratio (SINR) statisticson both uplink and downlink sides. These outputs can be evaluated in many different performance calculations.

The second LTE simulation includes the EPC network. Besides LTE helper module of NS-3, the EPC helper is also included. An IP stack is installed on each uE, then UDP server-client application is installed for each uE. In this simulation packet, transfers can be captured by NS-3 Flow Monitor module. Although flow monitor gives detailed network statistics on the application layer, it is complicated to implement, instead of that a set of probe functions developed to gather data in lower layers of NS3.

After the learning and simulator verification phases, an integration is performed on PSC-2.0 version of NS3. Because device to device PC5 interface availability it is a need to use that version. LTE coverage mode standard communication, sidelink in coverage mode, sidelink out of coverage mode examples simulated. For this simulation set, the focus is testing LTE out of coverage mode, which used PC5 direct interface in NS3. Base simulations have been performed to determine fundamental parameters that can affect network performance. To evaluate performance metrics we use m vehicle in a road simulation. n of m vehicle are included in intercommunication. In road simulation, every vehicle is created in a constant time interval with varied velocities. Vehicle movements are randomly assigned by SUMO. The used road model has enclosed square 2 line 2 way road as shown in Figure 5. Road simulation configurations can be seen in Table I. These two different configurations are defined to simulate short and middle distance communications. The duration of the simulation is 100 seconds. Gathering packet statistics starts after 32 seconds while all vehicles entered into the simulation. It means that all statistics are gathered with the exactly defined number of vehicles.

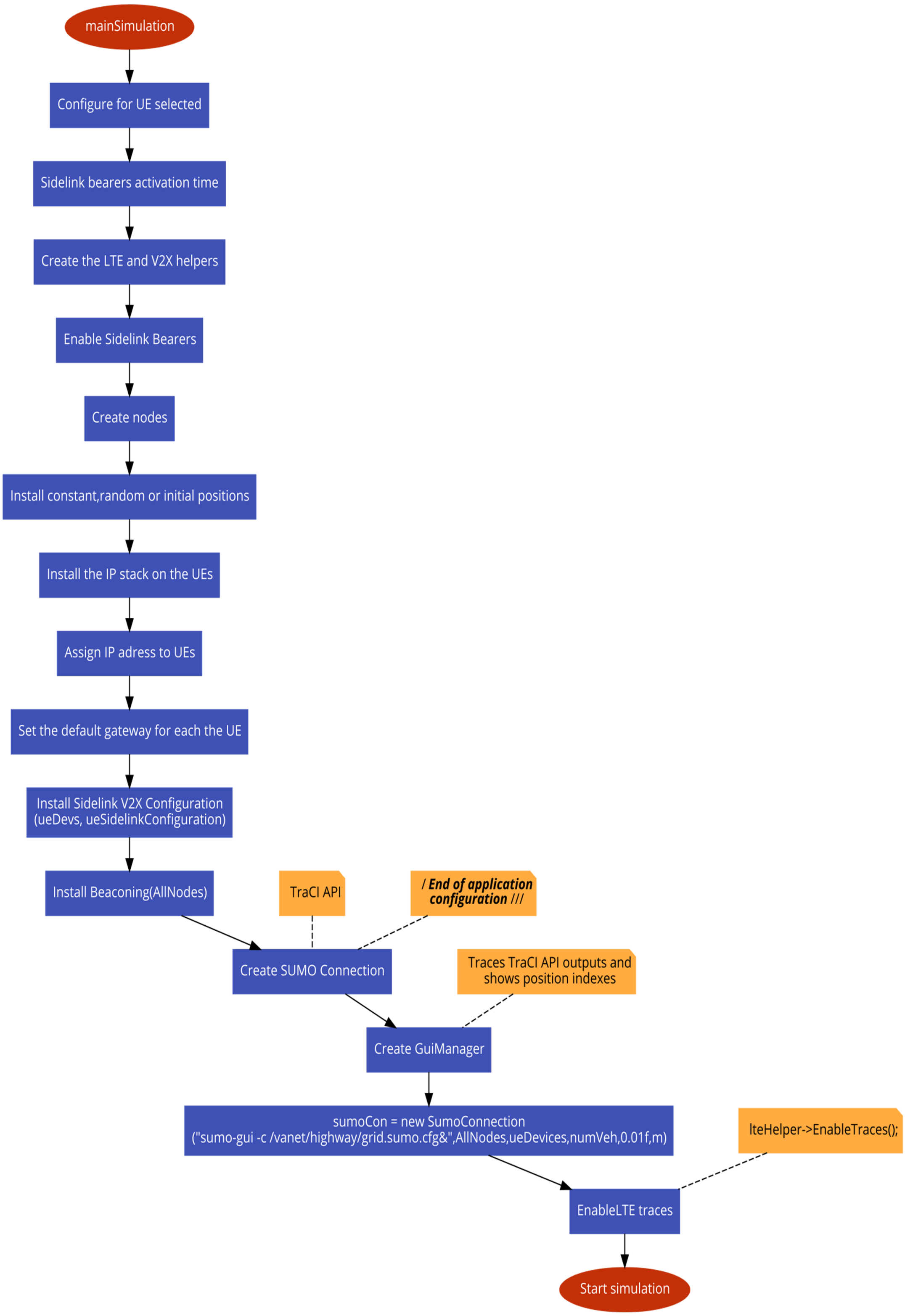

FIGURE 5.2 – NS-3 LTE V2X Main Program Flow

5.4 Contributed C-V2X Simulation Environment

NS3-PSC has ad-hoc communication, but NS3-PSC still does not cover specific vehicular communication features highlighted in Release 15. It supports LTE standard coverage models Mode 1, Mode 2, and a non standardized out-of-coverage ad-hoc mode. On top of NS3-PSC, an open source code (Eckermann et al., 2019) has been contributed to research on PC5 in Mode 3, Mode 4 communications and sensing based Semi Persistent Scheduling SPS as well as adjacent and non-adjacent resource block assignment, which are related to Mode 4. These implementations offer to simulate V2X scenarios.

This study's version of NS3-CV2X simulator offers another open source C-V2X simulation environment with different resource selection algorithm options, road scenarios, and PHY level configuration parameters to test new resource selection algorithms. A geo-based scheduled resource selection algorithm in (Molina-Masegosa et al., 2019), whose implementation details as a source code is not available in the open literature, is analyzed and implemented on top of C-V2X simulator (Eckermann et al., 2018). Geo-based scheduling is a technique in relation with vehicles' current geographic locations. Basically, it uses relative positions, calculates a vehicle's (V) closest neighbor vehicle (U) and assign a position index (PI) (Fig. 5.3) to assign a candidate RB (Fig. 5.4). $PI_V = PI_U + 1$; where PI_U, and it proposes lower packet collision rates in resource cell allocations (Molina-Masegosa et al., 2019). With the proposed new model in NS-3 simulation environment, packet reception rates, collusion cases, candidate RB usages and their probable SINR affects able to evaluate in LTE stack. Also analyzes can be performed both used SPS or without SPS in this simulation environment.

5.4.1 Parameters and Interfaces

As explained and detailed in (Rouil et al., 2017), a set of physical channel parameters can be tuned via software parameter interfaces. After evaluated the literature and several simulation examinations an enlarged input and output parameter set created. The developed simulation main program includes configuration parameters listed below :

— Simulation time in seconds : simTime (integer)

— Number of vehicles : numV (integer)

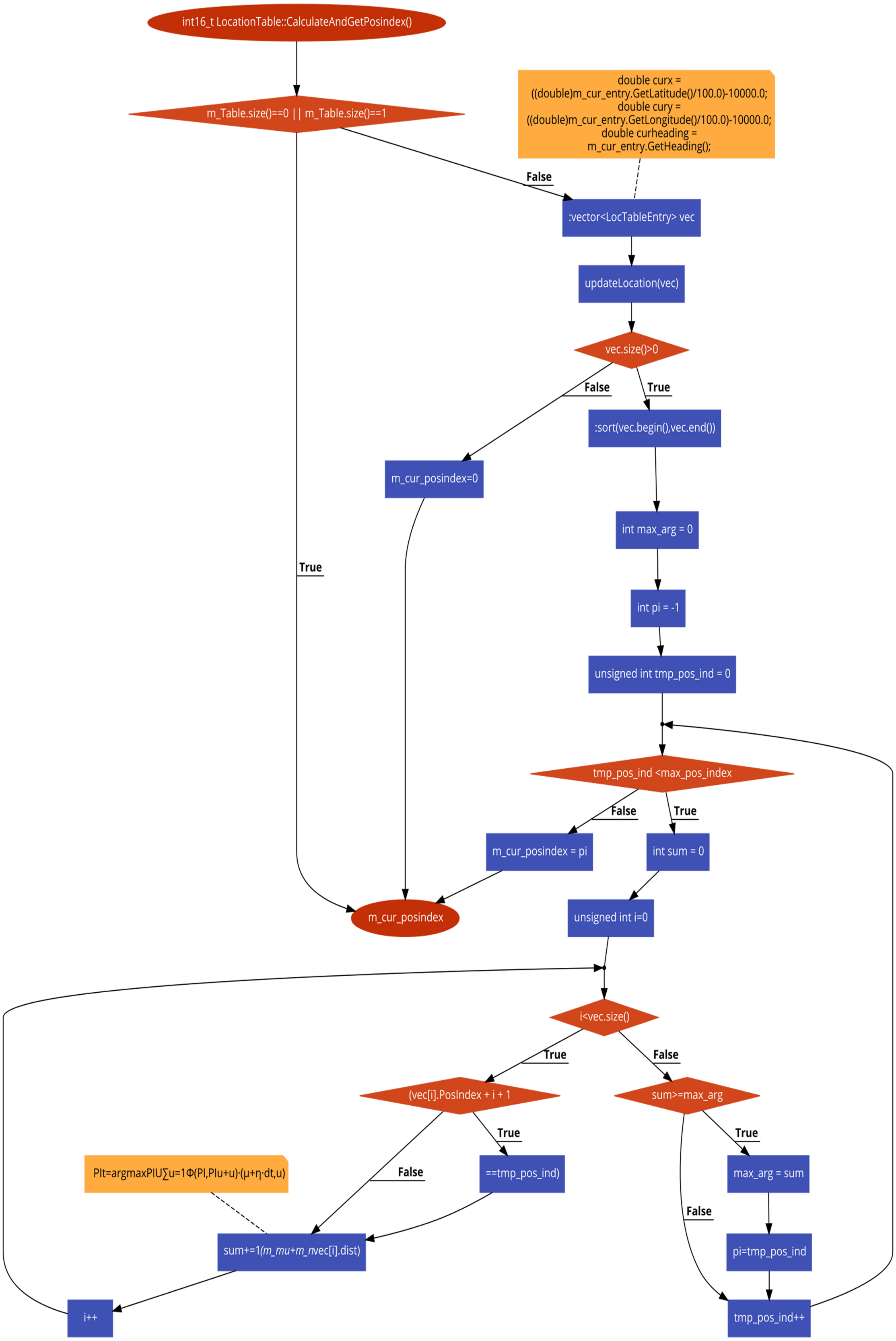

FIGURE 5.3 – Calculation of Position Index

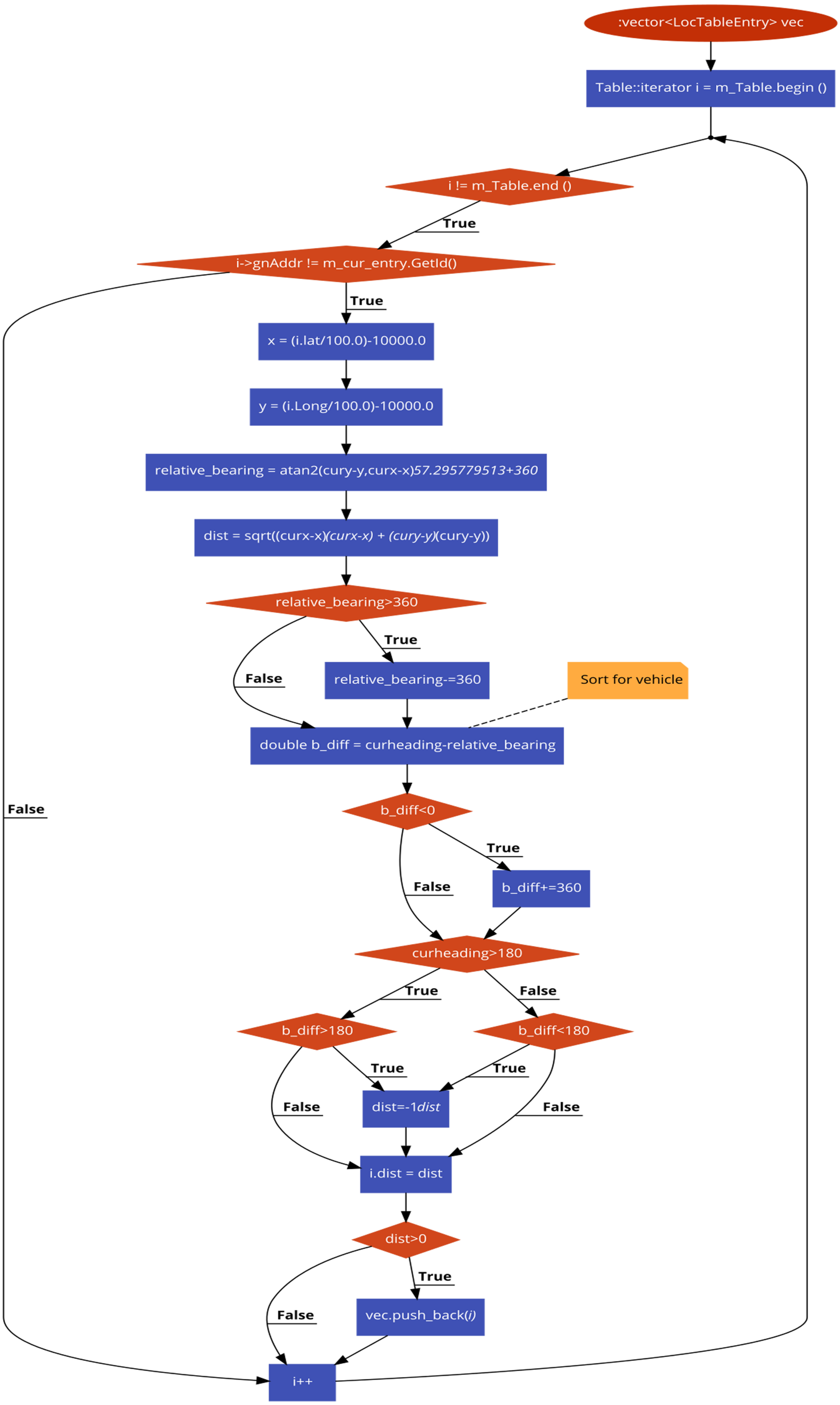

FIGURE 5.4 – Update Location Algorithm Flow

— Transmission power in dBm : ueTxPower (double)

— Accepted communication range : distLevel (integer)

— Probability to select the previous resource again [0.0-0.8] : probResourceKeep (double)

— Modulation and Coding Scheme : MCS (integer)

— Retransmission enabled : harqEnabled (boolean)

— Subchannelization scheme : adjacencyPscchPssch (boolean)

— Number of RBs per subchannel : sizeSubchannel (integer)

— Number of subchannels per subframe : numSubchannel (integer)

— Index of first RB corresponding to subchannelization : startRbSubchannel (integer)

— Resource reservation interval : pRsvp (integer)

— T1 value of selection window : t1 (integer)

— T2 value of selection window : t2 (integer)

— Sidelink bandwidth : slBandwidth (integer)

— SPS-based Scheduling Algorithm enabling : EnableSpsScheduling (boolean)

— Geo-based Scheduling Algorithm enabling : EnableGeoScheduling (boolean)

— Geo-based Scheduling Algorithm Index Shifting : posIdxShift (integer)

5.4.2 Simulation Outputs

While vehicular communication simulations need detailed analysis our simulation environment has several loggers that keep track of different network characteristics and messages.

PHY level logging is written into four different files which has a meaningful group of data. PHY level data :

— Simulation time in milliseconds

— Radio network temporary identifier (RNTI)

— Size of packet

— Modulating coding scheme (MCS)

— Bitmap identifier

— Block error rate

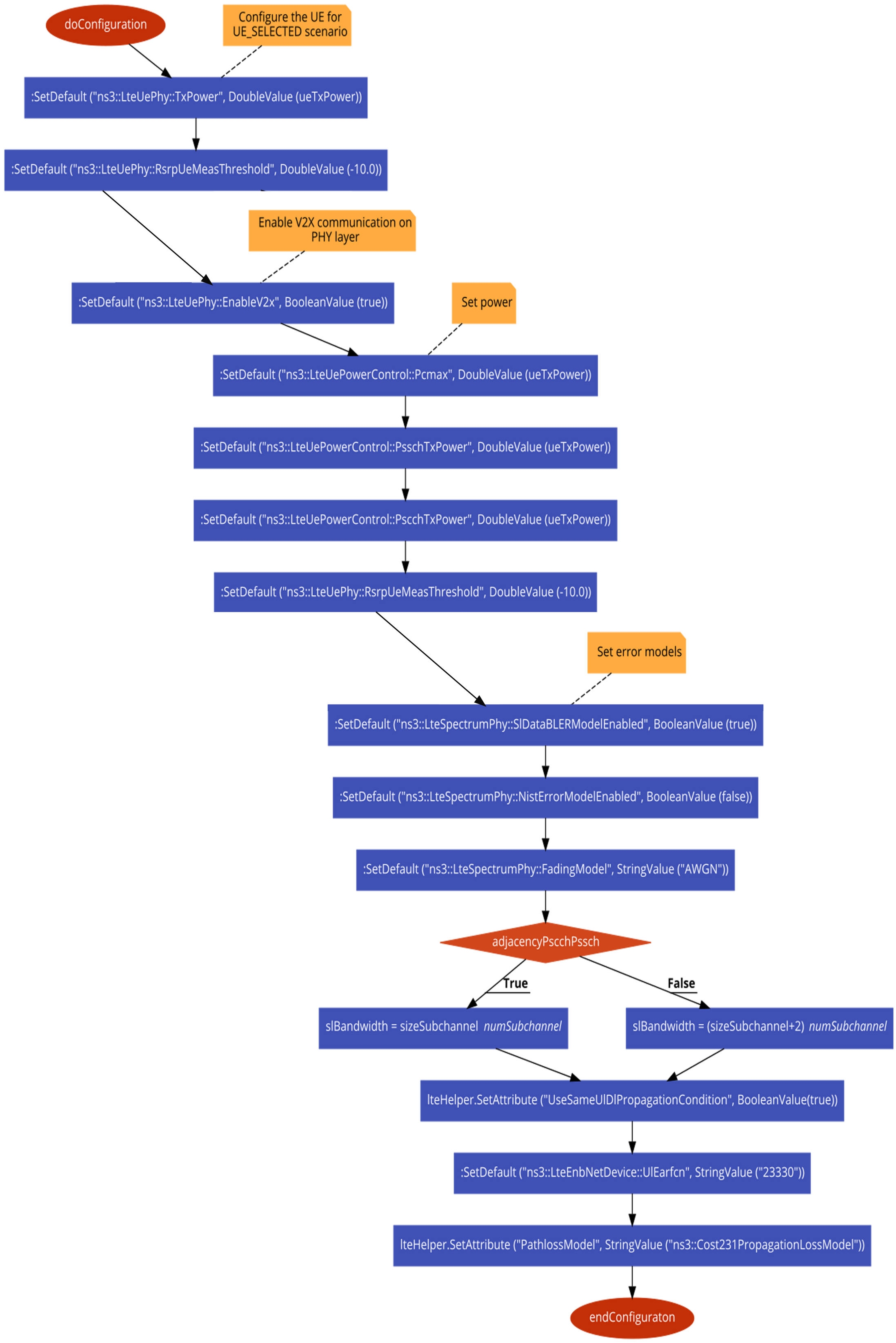

FIGURE 5.5 – NS-3 LTE Configuration Flow

— Corruption

— Allocated frame no

— Allocated subframe no

— Resource block (RB) start index

— RB length

— Sidelink received signal received power (RSRP in dBm) on allocated block

— Received message indication at specific resource block

Medium access controller (MAC) level information gathered into a single file which includes data :

— Selected resource

— RB start and length

— UE selected grant

— Subchannel length

— PSCCH Resource

— MCS

— Subframe Gap (SfGap)

— Retransmission index (0 default)

As the simulation environment is introduced both link level and system level simulator, it needs to provide system level gathered data :

— Simulation time in milliseconds

— Node id of evaluated node

— Node id of beacon/packet sent

— Timestamp of TX

— Distance between TX and RX nodes

— Latency in milliseconds

There are lots of extracted from the simulation environment and due to logging intervals, extracted data size more than 40 gigabytes. Analyzing each message and the whole case is not easy. Packet reception rates are the most important output for the evaluation. PRR calculations are done for the overall system and if there is a need for a PRR of a specified node, this can be parameterized. Besides node specific PRR calculation can be done according to the distance parameter, and active communication in that range is logged. These data are listed below logged in a single file.

— Simulation time in milliseconds

— Total Rx packets

— Total Tx packets

— Total Rx packets in specified distance

— PRR

— Node#1 Rx packets

— Node#1 Tx packets

— Node#1 active communication nodes

— Node#1 Rx packets in specified distance

— Node#2 Rx packets

— Node#2 Tx packets

— Node#2 active communication nodes

— Node#2 Rx packets in specified distance

— Node#3 Rx packets

— Node#3 Tx packets

— Node#3 active communication nodes

— Node#3 Rx packets in specified distance

6 SIMULATION STUDIES

6.1 LTE Out of Coverage Simulation

In this test set, simulations have been performed to determine fundamental parameters that can affect the network performance. m vehicles active in a traffic simulation, and all vehicles are included in intercommunication. In SUMO vehicles are created with varying velocity in a constant time interval. Vehicle movement is randomly assigned by SUMO. The used road map is an enclosed square having 2 ways and each way has 2 lines and its configuration parameters are given in Table 6.1. Overall, three different road topologies are created; a highway of 5 km having 6 lines (3 lines in each direction), a 3x3 Manhattan grid with 300 meters edges (total 900m x 900m square), and an enclosed square route with 800 meters edges, are used to analyze the performance. Gathering packet statistics starts after a while several vehicles are entered into the simulation and continues until reaching to the defined number of vehicles. To identify system bottlenecks, limitation, and to perform parameter

TABLE 6.1 – A List of Simulation Road Configuration Parameters

	Configuration
Total line length (km)	13,77
Side length (m)	800
Avg. speed (km/s)	47,86
Acceleration (m/s^2)	2,8
Deceleration (m/s^2)	4,5
Vehicle length (m)	3

optimization several simulation scenarios have been tested according to the hyper-parameter set shown in Table 6.2. In these tests, every vehicle sends broadcast messages in a specified constant time interval. Packet reception rate (PRR) extracted from ratio of received packet to transmitted packets. PRR is the main target which used for success rate in system level simulations. PRR is the function of different input parameters which are, the number of vehicles, packet size, packet interval (milliseconds). Besides PRR, packet delivery time or latency and channel utilization are the metrics which can be used to determine scalabity and robustness.

TABLE 6.2 – The List of Hyper-Parameters, Their Functions and Resolutions

Hyper-parameter	**Function**	**Interval Values**
Num. of Vehicle	Packet/Vehicle Density	20, 50, 100, 200, 300
Packet Interval (ms)	Packet Density	10, 20, 50, 100, 200
Packet size (bytes)	Throughput	200 , 300
nTRP	LTE PHY	1, 2, 4, 8
Resource Block Size	LTE PHY	2, 4, 8, 10
Sidelink Bandwidth	LTE PHY	30, 50, 100
Sidelink Period	LTE PHY	40, 120, 240, 320
Carrier Frequency	LTE PHY	18100, 23330, 54990
MCS	LTE PHY	5, 10, 15, 20

These output metrics are generally affected by modulation and coding scheme (MCS), resource block size (RB), number of transmissions opportunities in a time repetition pattern (nTRP), PSSCH length, sidelink number of subframes (nSF), carrier frequency and sidelink bandwidth parameters. Packet loss on a node is strongly correlated to RX packet density over this node. The number of packets in a system can be changed in two ways. The first one is altering TX time intervals and the other one is increasing or decreasing the number of vehicular nodes. Although packet reception rates (PRR) are changed by the total number of packets in network, the number of vehicles parameter has more impact due to higher collision probability of near nodes. It means that sending m packet from n vehicle, does not give same output sending one packet from m*n vehicle. As it is illustrated in (Fig. 6.1), decreasing

the number of vehicle affects packet density and PRR correlative. And collision on a single channel can cause these packet drop rates. In compliance with specifications, messages cannot be received in case of being in TX mode or RB allocation collision occurs. Thus, on RX mode high overlap probability is exists. The collision probability is calculated by a formula $p_c = 1 - (1 - 2/N_{RB}N_{sf})^{N_n - 1}$ (Eckermann et al., 2018). When investigating the physical layer (PHY), parameters are related to correct channel configurations where some combinations may cause unreasonable packet loss. Such parameters should be simulated to satisfy system requirements. When these tests are performed, other parameters have been chosen according to worst-case scenarios to highlight tested parameter impacts. For example,it is seen that, for 100 millisecond packet intervals nTRP = 4 performed well, but for 10 ms intervals nTRP = 2 has better performance. The relation between RB size and nTRP has an impact on packet loss as shown in Table 6.3. The sidelink period in milliseconds (SF) has a

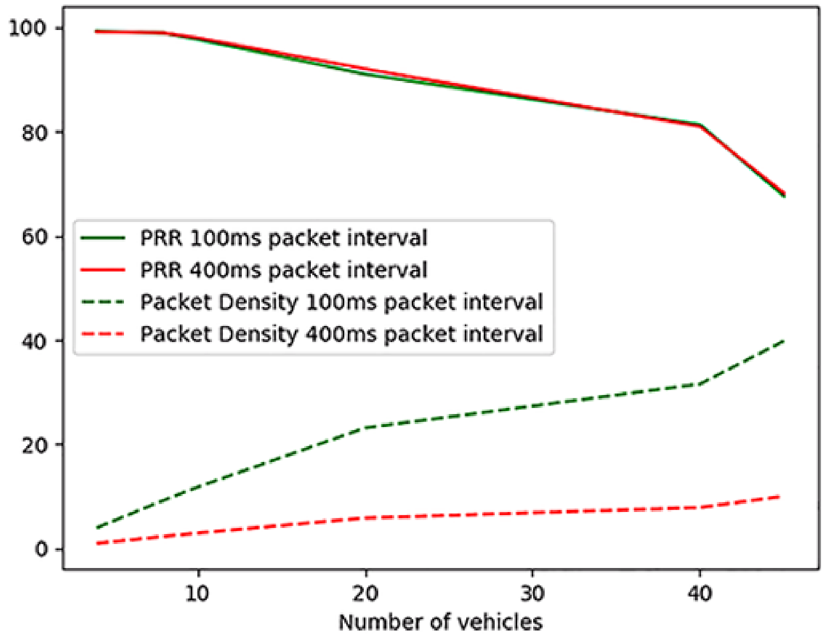

FIGURE 6.1 – Relations between packet density and PRR due to number of vehicles

minor effect on performance with parameters sf40, sf120, sf240, and sf320. Different modulation and coding scheme options can be applied for analysis. MCS is one of the most channel configuration parameters which affects transmitting distance and packet loss rate due to coding error. The parameter set, is shared in the study (Bazzi et al., 2019) in Table 4, is used in simulations for MCS optimizations. MCS index explanations are given in 3GPP TSG-RAN R1-081483 document (Europe, 2008). Observations over MCS shows that lower MCS index can allow farther transmits but with lower signal resolutions.

The outputs gathered from the first simulation set show that packet loss occurs subject to vehicle density and parameter optimization on the physical layer may maximize the performance of the overall system. LTE physical layer needs convenient parameter assignments to perform well at out of coverage scenarios.

TABLE 6.3 – Resource blocks and number of TRP effects on packet loss

RB Size	nTRP	Packet Loss	RB Size	nTRP	Packet Loss
8	1	19,58%	2	4	12,69%
8	2	15,25%	4	4	17,07%
8	4	10,44%	8	4	8,94%
8	8	36,84%	10	4	12,11%

Packet loss on server occurs because of collision on that sidelink channel configurations. For example, if the results on lines 2 and 3 in Table 6.4 are compared, despite of increased

bandwidth, packet loss increased. From the comparison of line 1 and 2, the effect of ulEarfcn could not be resolved. As many tests show that ulEarfcn 18100 and 23330 performs similarly but the results did not match the expected theoretical values mentioned in several studies. The maximum packet loss is 13% on our simulation scenarios, in which maximum throughput is 153 Mbps.

TABLE 6.4 – Bandwidth Relation with Packet Loss

Packet Interval (sec)	ulEarfcn	UL Bandwidth	Packet Loss
0,05	23330	50	8,89%
0,05	18100	50	8,74%
0,05	18100	100	9,23%
0,02	18100	100	9,273%

Following the performance changes with respect to the parameters such as packet size, MCS, RB size, nTRP in the enclosed square route with 800 meters edges, are optimized as declared in Table 6.5.

TABLE 6.5 – Applied LTE physical channel configuration parameters

nTRP	4
RB Size	10
PSSCH Length	8
SL UL Bandwidth	50
SF Period	sf320
Sidelink Ch. Freq.	23330
MCS	10
TX Power (dBm)	23.0

6.2 C-V2X System Level Simulations

In the C-V2X System Level test scenario, when a vehicle is penetrated, it starts broadcasting within a given time intervals. Every vehicle receives broadcasted packets in the specified antenna transmission range. Transmission range PRR analysis have performed in highway road topology. The other SPS only, geo-based only and SPS enhanced with geo-based forms RB selection algorithms are compared in different scenarios. As the SPS scheduling is the key technique on Mode 4 of C-V2X, in all different road scenarios it performs well. The performed simulation results are given in Table 6.6. For this test set, MCS parameter is assigned as 20. Thereby, physical layer configuration optimization is eliminated and algorithm performances can be evaluated.

TABLE 6.6 – C-V2X Simulation Results

	Manhattan		**Closed Square**		**Highway**	
	100 veh/km		50 veh/km		100 veh/km	
TX-RX Dist.	*50m*	*100m*	*100m*	*200m*	*100m*	*200m*
SPS	1	0.9991	0.9924	0.97	1	0,96
Geo-based	1	0.966	0.84242	0.7534	1	0.94
Geo + SPS	1	0.96	0.84242	0.7617	1	0.944

After evaluation of these outputs geo-based algorithm performs well but not better than SPS algorithm. The derived geo-based scheduling algorithm have an acceptable performance for PRR in different scenarios up to 2% improvement in comparison with the reference geo-based scheduling algorithm. The other important evaluation metrics are channel busy ratio (CBR) and cell block utilization (CBU), as described in (Karoui et al., 2020). In congested network they have significant role in robustness. Geo-based scheduling used cell blocks of implemented geo-based algorithms are shown in Fig. 6.2 in red lines.

Proposed resource block allocation is more successful in terms of normal distribution of candidate positions index, since neighbor vehicle should select farther RB in the pool. But, collision probability does not improved. Our derivation on prior geo-based algorithm is shifting position index by m in same pool. If the pool size is exceed then continue shifting from start index of the pool "0". While just a spacing is added on top of it, relative positioning logic still exists. The distribution of position indexes with derived geo-based algorithm are shown in Fig. 6.2.

Increasing the full range of position index distribution has a positive effect on SINR values and also collision probability is decreased. SINR values affect the SPS selection algorithm.

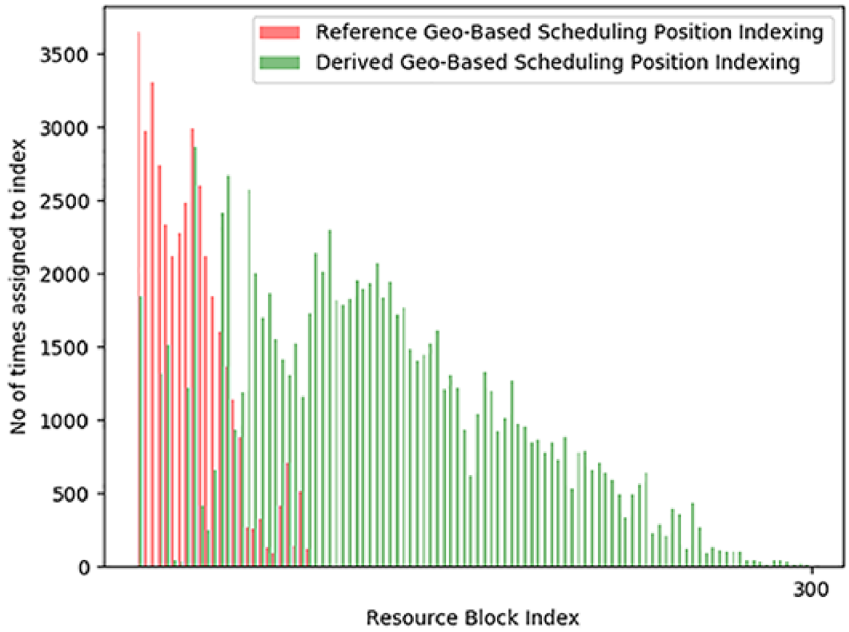

FIGURE 6.2 – Geo-Based Scheduling Position Index Distributions

And also another subject of the performance metric is link layer performance, which can be evaluated with a BLER/SNR ratio. Although it is related to LTE physical channel specifications, due to the relation of resource selection and signal distribution on each RB differs in each algorithm. In a scenario with high vehicle density, increasing total noise power on each cell affects the SINR negatively. The geo-based scheduling algorithm also spread this noise power. In terms of end-to-end delay, results are changed from 4ms to 204 ms with an average 54 ms for different scenarios. RSSI measurements distributed between -138.786 dBm and -44 dBm as the defined range of RSRP is -140dBm to -44dBm in RSRP mapping 3GPP TS 36.133 V8.9.0. The majority of RSSI measurements are higher than -85 dBm which indicates good and excellent signal strengths.

Another important physical layer parameter is MCS. It affects transmit distance capability. Lower indexed MCS parameter can transmit in longer distances, but in contrast error rates (1% - 2%) and latency (1ms - 2ms) are increased. As a channel quality indicator (CQI) metric MCS is also related with SINR. In Fig. 6.3 proposed algorithm tested with different vehicle densities and MCS. It gives an overall view of system level simulation for C-V2X scenarios.

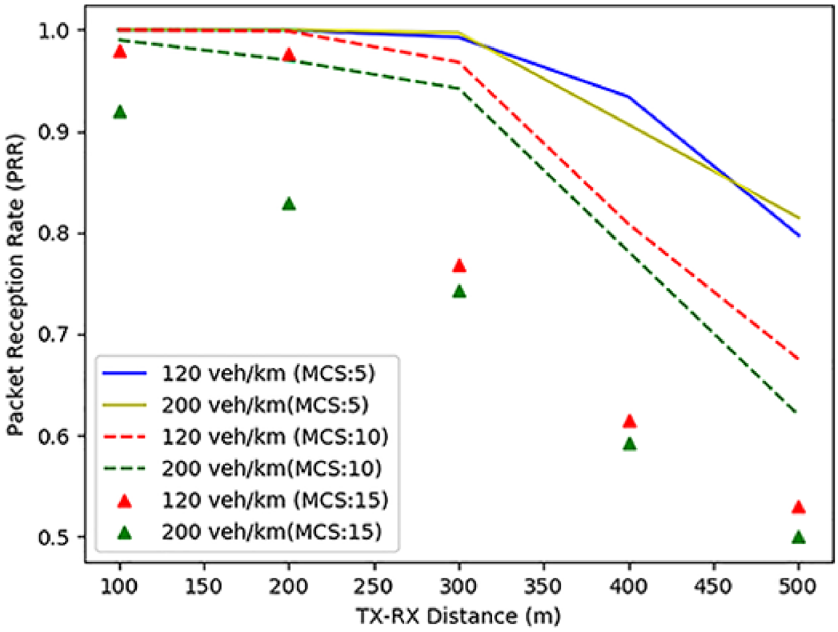

FIGURE 6.3 – PRR and TX-RX distance relation

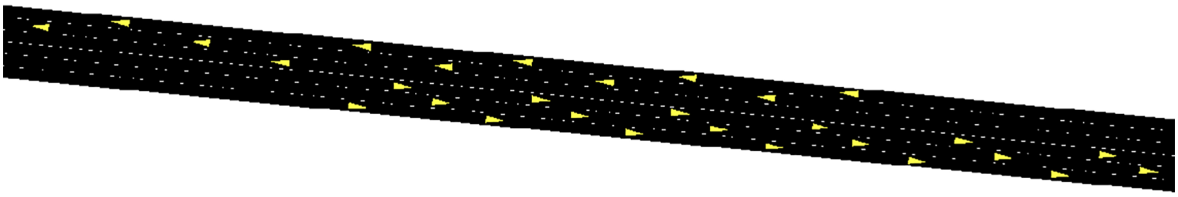

FIGURE 6.4 – SUMO Highway Road Model

6.2.1 C-V2X Simulations with Different Road Topologies

For the system level simulations, four different road types have been constructed with netedit. Implemented road models are highway Fig. 6.4, Manhattan district Fig. 6.5, 4 way intersection point with traffic lights Fig. 6.6 and a non-line-of-sight (NLOS) Fig. 6.7 turn.

In vehicular communication test scenarios, number of vehicle per kilometers is important parameter in simulation and also it is related with number of lanes in existing model. To do so in highway model each vehicle's departure speed have been assigned with 108 km/h (30m/s), 72 km/h (20m/s), 54 km/h (15m/s) for different simulations. In urban models that

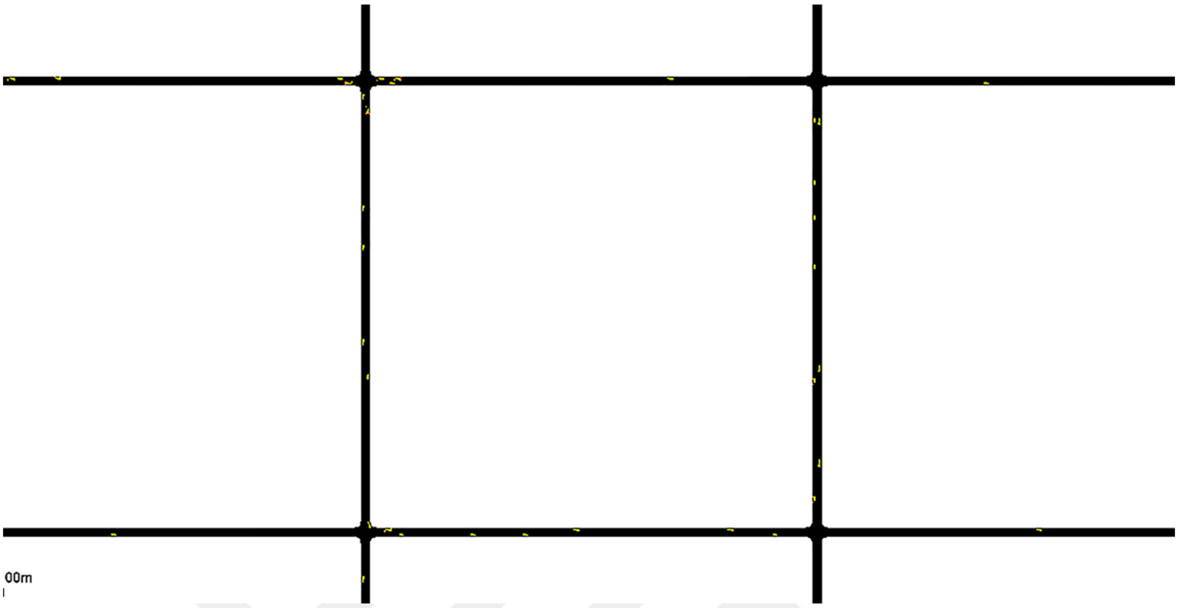

FIGURE 6.5 – SUMO Manhattan Road Model

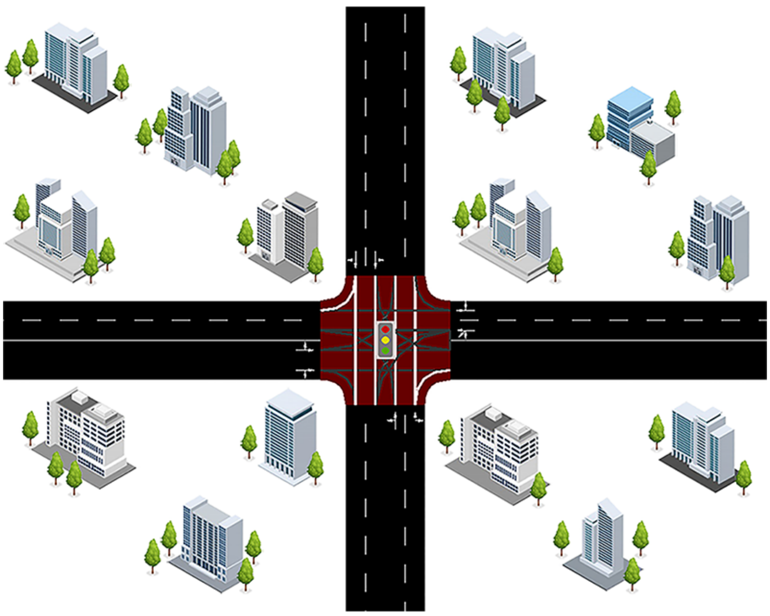

FIGURE 6.6 – SUMO Intersection Road Model

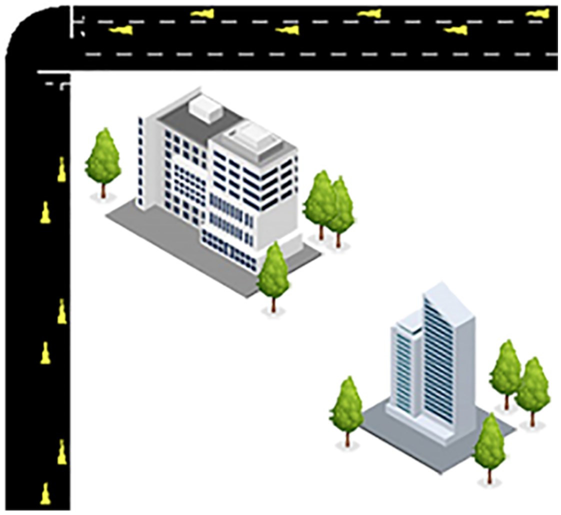

FIGURE 6.7 – SUMO NLOS Road Model

TABLE 6.7 – C-V2X Road Topology Simulation Results

Road Topology	**PRR**	**Latency (ms)**
Highway	0.982	69.3
Manhattan	0.999	62.6
Intersection	0.999	63
NLOS	0.986	72

are Manhattan district, intersection, NLOS turn, speed parameters have been set as 36 km/h (10 m/s), 18 km/h (5 m/s), 10,8 km/h (3 m/s).

In highway model 1500 meters 3 lane - 2 way road configuration is used. One line of both directions assigned to trucks usages only. In urban scenarios,all vehicle types are declared as a car. Manhattan model consist of 3x3 in total of nine blocks. Each edges of blocks are 300 meter long without traffic lights. For none line of sight model, 2 line - 2 way road model with 300 meter long edges is created. In this topology vehicles destructed at the end of the edges to simulate NLOS effect correctly. Intersection model consist of four 2 lane- 2 way edges with 300 meters long. On the intersection of them traffic lights enabled, and crossing priorities are assigned in equal.

In urban models communication distance declared as 100 meters long, in highway topology 300 meters long. For all topologies' analysis conducted with respect to PRR and latency listed in Table 6.7.

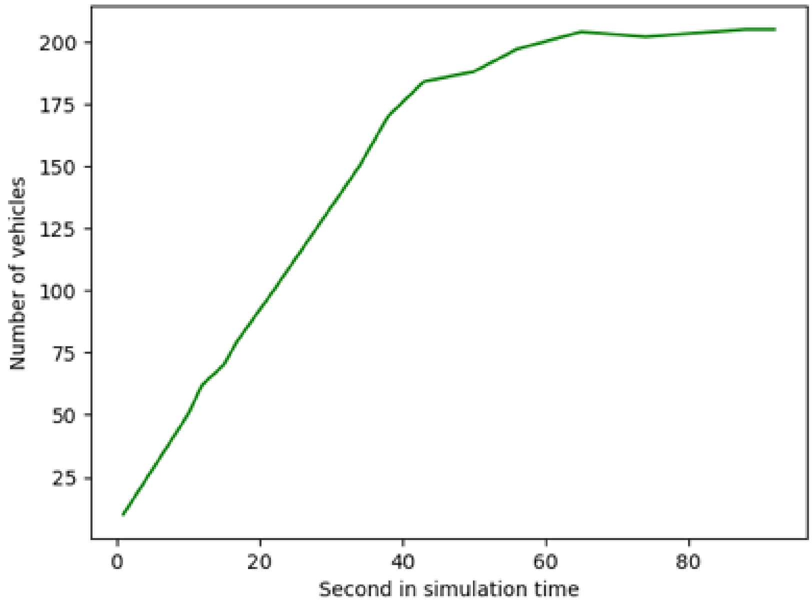

FIGURE 6.8 – Number of vehicle in simulation at specified time

Use case scenarios includes several radio resource configurations with fastest speeds on highway : 108 km/h - urban : 36 km/h and slowest speeds highway : 54 km/h - urban : 10.8 km/h. The other difference between urban and highway topologies is path-loss mode. To simulate more realistic scenarios, channel models are set as the COST 231 model in highway simulation and the Nakagami model in urban area simulations. As an example of number of vehicles communicate in simulation at specified time can be seen in Fig. 6.8.

The overall results shows that PRR and latency outputs are promising in different topologies. Tests have been performed conform to the 3GPP's V2X use case scenarios. Higher PRR for highway and NLOS can be achieved by decreasing number of vehicles in simulation. Latency results are average values where in some messaging 4 ms per-to-peer latency have been achieved.

7 CONCLUSION

After evaluations of simulation outputs, resource block size (RBs), number of transmissions opportunities in a time repetition pattern (nTRP), number of PSCCH subframes, length of sidelink period in milliseconds and its relation with packet inter-arrival time are key factors for packet reception ratio. Modulation coding scheme is one of the key factors for transmitting distance besides antenna power, also affects the performance in some specific cases. Vehicular network simulations show that vehicular density is the main reason for network performance attenuation. Packet intervals, packet density also affects the performance.

Resource selection is a major bottleneck of C-V2X Mode 4 in urban or traffic dense areas, and resource selection scenarios can be built up on top of these base parameters. The proposed changes in the resources selection algorithm perform well and competitive when compared with existing algorithms in terms of PRR and resource cell selection distribution. The proposed algorithm has a weak performance in Manhattan district scenarios due to direction calculation problems in geo-based scheduling algorithm design. Although it gives good results, it should be improved by taking vehicle directions into account to select a resource block. Given hyper-parameter set and resource selection algorithms have promising improvements on the link- quality and the link-performance models overall. Nor in this simulation study nor other researches in literature do not provide 90% PRR results around 500m ranges. According to theoretical calculations, with the C-V2X enhancements in VANET, vehicles should communicate within at least 500m with high packet delivery ratios in a robust environment.

The latest 3GPP releases may present new specifications, which propose new physical channel implementations with feedback channel, extended modulation coding schemes, additional resource scheduling techniques and New Radio (NR) 5G implementation. NR-5G simulator requires more challenging developments to be validated in certain use cases. Besides the NR 5G, this study presents different resource selection algorithm implementation interfaces and also filtered broadcast options in the application layer. For further research, feedback channel implementation and unicast/groupcast options on transport layer should be completed. Also, resource selection by leveraging machine learning and platooning clustering algorithms are other opportunities to study. Many different test scenarios and parameter sets can be combined and analyzed with intelligent systems. Performance maximization works for particular system requirements can be enhanced with this publicly available test environment.

C-V2X technologies emerge to new vehicle usage experiences with enhanced road safety, safer autonomous driving applications, and new mobile customer services with collaboration of machine learning, edge computing, precise positioning and sensor technologies. For all of these V2X developments needs to the cooperation of automotive industry, government authorities, mobile operators, telecom companies, and academia.

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APPENDIX A 3GPP RELEASES AND RELEASE DETAILS

Table APPENDIX A.1

3GPP Release	**Release date**	**Details**
Phase 1	1992	Basic GSM
Phase 2	1995	GSM features including EFR Codec
Release 96	Q1 1997	GSM Updates, 14.4 kbps user data
Release 97	Q1 1998	GSM additional features, GPRS
Release 98	Q1 1999	GSM additional features, GPRS for PCS 1900, AMR, EDGE
Release 99	Q1 2000	3G UMTS incorporating WCDMA radio access
Release 4	Q2 2001	UMTS all-IP Core Network
Release 5	Q1 2002	IMS and HSDPA
Release 6	Q4 2004	HSUPA, MBMS, IMS enhancements, Push to Talk over Cellular, operation with WLAN
Release 7	Q4 2007	Improvements in QoS & latency, VoIP, HSPA+, NFC integration, EDGE Evolution
Release 8	Q4 2008	Introduction of LTE, SAE, OFDMA, MIMO, Dual Cell HSDPA
Release 9	Q4 2009	WiMAX / LTE / UMTS interoperability, Dual Cell HSDPA with MIMO, Dual Cell HSUPA,LTE HeNB
Release 10	Q1 2011	LTE-Advanced, Backwards compatibility with Release 8(LTE), Multi-Cell HSDPA
Release 11	Q3 2012	Heterogeneous networks (HetNet), Coordinated Multipoint (CoMP), In device Coexistence (IDC), Advanced IP interconnection of Services,
Release 12	March 2015	Enhanced Small Cells operation, Carrier Aggregation(2 uplink carriers, 3 downlink carriers, FDD/TDD), MIMO (3D channel modelling, elevation beamforming,massive MIMO), MTC - UE Cat 0 introduced, D2D communication, eMBMS enhancements.
Release 13	Q1 2016	LTE-U / LTE-LAA, LTE-M, Elevation beamforming Full Dimension MIMO, Indoor positioning, LTE-M Cat 1.4MHz & Cat 200kHz introduced
Release 14	Mid 2017	Elements on road to 5G
Release 15	End 2018	5G Phase 1 specification
Release 16	2020	5G Phase 2 specification
Release 17	∼Sept 2021	
Release 18	∼2023	

(*) https://www.electronics-notes.com/articles/connectivity/3gpp/standards-releases.php

APPENDIX B SIMULATION SCENARIO DEFINITION

Simulation: (Example)

Time (sec): 100

Vehicle

- Number of vehicles : 8 / 10 / 16 (two different communication groups),
- Number of lanes in one direction : 2 * Vehicle types and velocities can vary
- Road : Closed rectangle road, two-lined two-way highway, closed 8-type road

Packet:

- Data size (bytes) : 100/200
- Data Type : Dummy/CAM/DENM
- Interval (sec) : 0.01 $\rightarrow$ 0,4

Network:

- Mode : Mode 2 (3GPP Release 12), Mode 4 (Rel.15) *Mode 1 and Mode 3 can be used for performance comparisons in network coverage scenarios

Physical Layer:

- Modulation and Coding Scheme (MCS) : 10 / 16
- Resource Block (RB) Size : 2,4,8,10
- Transmission opportunities in a Time Repetition Pattern (kTRP) : 2 / 4 / 8(number of subframes to transmit on)
- PSCCH Length : 8
- PSCCH Period : sf40 (40ms) (related with data interval for optimization)
- Number of Pools : 1
- Carrier Frequency : 18100/23300
- Sidelink Bandwidth : 50 / 100
- LTE UE Phy Tx Power : 23 dBm (Lower power levels also will be investigated)

— LTE UE Power Control (max) : 23 dBm

— LTE UEPSSCH Tx Power : 23 dBm

— Sidelink Control Error Model Enabled : True

— Sidelink Data Error Model Enabled : True

— Drop RB on Collision Enabled :False

— Pathloss Model : None (Cost231, RandomPropagation, Friis, LogDistance, Nakagami, Range)

Expected Outputs:

— Packet Reception Ratio (PRR)

— Latency

— Throughput

— Interarrival of Received Packets (IAT)

— Collision Probability : (Expected value according to the input parameters) *Collusion Probability formula

Discussion:

— Scalability

— Reliability

— Confidence interval

APPENDIX C SUMO CONFIGURATION FILES

Highway Scenario

Example highway.rou.xml content:

vType id="normal_car" vClass="passenger" maxSpeed="32"
speedFactor="0.9" speedDev="0.2" sigma="0.5"
vType id="trailer" vClass="coach" maxSpeed="20"
speedFactor="1.1"speedDev="0.1"
route edges="-gneE3" color="yellow" id="route_0"
route edges="gneE3" color="yellow" id="route_1"
route edges="-gneE3" color="green" id="route_0_1"
route edges="gneE3" color="green" id="route_1_1"

flow id="normal1" type="normal_car" route="route_0" departLane="random"
departSpeed="25" begin="0" end="10" number="220"
flow id="normal2" type="normal_car" route="route_1" departLane="random"
departSpeed="30" begin="0" end="10" number="210"
flow id="platoon_1" type="trailer" route="route_0_1" departLane="first"
departSpeed="20" begin="0" end="10" number="32"
flow id="platoon_2" type="trailer" route="route_1_1" departLane="first"
departSpeed="20" begin="0" end="10" number="38"

Example highway.net.xml

edge id="-gneE3" from="gneJ7" to="gneJ6" priority="-1"
lane id="-gneE3_0" index="0" speed="130.89" length="1347.66"
shape="1702.97,-1234.02 357.29,-1102.73" density="100"
lane id="-gneE3_1" index="1" speed="90.89" length="1347.66"
shape="1702.87,-1237.22 357.20,-1105.93" density="100"
lane id="-gneE3_2" index="2" speed="90.89" length="1347.66"
shape="1702.78,-1240.41 357.10,-1109.13" density="100"

edge id="gneE3" from="gneJ6" to="gneJ7" priority="-1"

lane id="gneE3_0" index="0" speed="130.89" length="1347.66"

shape="356.81,-1118.72 1702.49,-1250.01" density="100"

lane id="gneE3_1" index="1" speed="90.89" length="1347.66"

shape="356.91,-1115.52 1702.58,-1246.81" density="100"

lane id="gneE3_2" index="2" speed="90.89" length="1347.66"

shape="357.00,-1112.32 1702.68,-1243.61" density="100"

junction id="gneJ6" type="dead_end" x="357.05" y="-1110.72"

incLanes="-gneE3_0 -gneE3_1 -gneE3_2" intLanes="" shape="357.05,

-1110.72 357.34,-1101.13 357.05,-1110.72"

junction id="gneJ7" type="dead_end" x="1702.73" y="-1242.01"

incLanes="gneE3_0 gneE3_1 gneE3_2" intLanes="" shape="1702.73,

-1242.01 1702.44,-1251.61 1702.73,-1242.01"

Example highway.sumo.cfg: -configuration

-input

net-file value="hghway.net.xml"

route-files value="hghway.rou.xml"

/input

-time

begin value="0"

end value="100"

step-length value="0.01"

/time

traci_server remote-port value="8888" /traci_server

/configuration-