

UNIVERSIDADE FEDERAL DO PARANÁ

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INCORPORATING THE GEMV2 GEOMETRY-BASED VEHICLE-TO-VEHICLE RADIO
PROPAGATION CHANNEL MODEL INTO THE ARTERY SIMULATION FRAMEWORK
FOR VANET APPLICATIONS

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Dissertação apresentada aos cursos de Pós-Graduação em Engenharia Elétrica, Setor de Ciências Exatas, Universidade Federal do Paraná e em Engenharia Automotiva Internacional, Faculdade de Engenharia Elétrica e Ciências da Computação, Technische Hochschule Ingolstadt como requisito parcial à obtenção dos títulos de Mestre em Engenharia Elétrica e Master em Engenharia Automotiva.

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Coorientador: Prof. Dr. Christian Facchi

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To my family, Valdirene, Edilson and Aline.

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RESUMO

A comunicação veicular tem como principal objetivo a otimização do tráfego e a diminuição de acidentes nas estradas. Como trata-se de um item de segurança, é necessário que o sistema seja massivamente testado em diversas situações possíveis antes de ser colocado em prática, o que tornaria a aplicação inviável devido ao elevado custo e ao tempo. Através de simuladores computacionais é possível realizar essa operação mais eficientemente assim como confibializar o sistema como um todo. Para isso é necessário que o simulador veicular possua uma precisão mais próxima da realidade possível com uma alta escalabilidade, entretanto, com um processo computacional executável.

Nesse contexto, essa dissertação tem o objetivo de tornar o ambiente virtual mais realístico através da implantação de um modelo de rádio propagação propício para o ambiente veicular, o qual diferencia dos modelos tradicionais devido à alta mobilidade dos comunicantes (carros) em alta velocidade e o impacto dos mesmos na comunicação. Como simulador, foi utilizado o framework de simulação Artery, o qual é uma extensão melhorada do VEINS uma vez que agrega as funcionalidades de comunicação europeia VANET no mesmo e aumenta sua escalabilidade. Além disso o Artery faz uso do Vanetza, o qual é responsável pela implementação da pilha de protocolo do ETSI ITS-G5. Tanto o Artery e Vanetza são desenvolvidos sob a plataforma Omnet++ e possuem licença de código aberto.

O GEMV² é um modelo de rádio propagação determinístico e estocástico, o qual considera o impacto dos demais veículos sobre o canal de comunicação veicular. Além disso, apresenta um modelo eficiente para realísticas simulações em larga escala com milhares de veículos comunicantes em vários ambientes veiculares (urbano, rural, rodovia). Além disso apresenta um ótimo *tradeoff* entre escalabilidade e precisão, tendo seu modelo validado através de medições de campo.

Após a implementação do modelo GEMV² na estrutura de simulação Artery constatou-se uma alta sensibilidade do mesmo para variações no posicionamento da antena e do carro por si só, e assim como previsto, uma melhora aproximadamente de 82,3 dB na potência recebida se comparado com modelos tradicionais de rádio propagação usados até então no Artery, justificados pelas considerações geométricas que o modelo aplica.

Palavras-chave: VANET, Artery, GEMV², modelo de rádio propagação veicular, framework de simulação. Omnet. MATLAB.

ABSTRACT

The main goal of vehicular communication is the traffic optimization and the reduction of accidents on the roads. Since it is a safety item, it is recommended that the system is massively tested in several possible situations before being put into practice, which would become the application infeasible due to the high cost and time. Through computer simulations, it is possible to perform these operations more efficiently as well as getting the whole system more trustworthy. That said, it is necessary that the network and traffic based vehicular simulator has an accuracy as close to reality as possible and with a high scalability, however, with an executable computational process.

As for the simulator, the Artery simulation framework was used, which is based on VEINS and enhances this by adding the European VANET communication functionality and by increasing its scalability. In addition, Artery makes use of Vanetza, which is an implementation of the ETSI ITS-G5 protocol stack. Both Artery and Vanetza were developed under the Omnet ++ platform as open source.

In this context, this dissertation aims to become the virtual environment more realistic by implementing a radio propagation model that fits the vehicular environment, which differentiates from the traditional models due to the high mobility of the communicators (vehicles) at high speed and their impact over the communication channel.

The GEMV² is a deterministic and stochastic radio propagation model, which considers the impact of the other vehicles over the vehicular communication channel. In addition, it presents an efficient model for realistic large-scale simulations with thousands of communicating vehicles in various vehicular environments (urban, rural, highway). Furthermore, it can achieve a good scalability/accuracy tradeoff, having its model validated through extensive field measurements.

After the implementation of the GEMV² model into the Artery simulation framework was noticed that the model has a high sensitive in relation to the antenna position and the vehicle's positioning itself. Moreover, as expected, an improvement of approximately 82.3 dB at received power emerged if compared to the traditional radio propagation models used by Artery till then, justified by the geometric considerations that the model applies.

Keywords: VANET, Artery, GEMV², vehicular radio propagation model, simulation framework. Omnet. MATLAB.

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LIST OF ABBREVIATIONS

| | |
|-------------------|-----------------------------------------------------------------|
| AC | Access Categories |
| ASTM | American Society for Testing and Material |
| DSRC | Dedicated Short Range Communication |
| EDCA | Enhanced Distributed Channel Access |
| FCC | Federal Communication Commission |
| FE | Free Space |
| GEMV ² | Geometry-based Efficient Propagation Model for V2V |
| IEEE | Institute of Electrical and Electronics Engineers |
| IP | Internet Protocol |
| ITS | Intelligent Transportation Systems |
| LLC | Logic Link Control |
| LOS | Line of Sight |
| LuST | Luxembourg Sumo Traffic |
| MAC | Medium Access Control |
| MANET | Mobile Ad Hoc Networks |
| MONARCH | Mobile Networking Architectures |
| NHTSA | National Highway Traffic Safety Administration |
| NLOS | Non-Line of Sight |
| NLOS _b | Non-Line of Sight due to Buildings |
| NLOS _v | Non-Line of Sight due to Vehicles |
| PHY | Physical |
| RSU | Roadside Unit |
| SIMTD | <i>Sichere und Intelligente Mobilität- Testfeld Deutschland</i> |
| STRAW | Street Random Waypoint |
| SUMO | Simulation of Urban Mobility |
| TCP | Transmission Control Protocol |
| TEXAS | Traffic Experimental and Analytical Simulation |
| TRG | Two-Rays Ground |
| UDP | User Datagram Protocol |

| | |
|-------|------------------------------------------------|
| UFPR | Universidade Federal do Paraná |
| USDOT | United State Department of Transportation |
| V2M | Vehicle to Motorcycle |
| V2V | Vehicle to Vehicle |
| V2I | Vehicle to Infrastructure |
| V2P | Vehicle to Pedestrian |
| VANET | Vehicle Ad Hoc Networks |
| WAVE | Wireless Access in the vehicular Environmental |
| WSM | Wave Short Message |
| WSMP | Wave Short Message Protocol |

LIST OF SYMBOLS

| | |
|-----------|-------------------------------------------|
| d | Distance |
| E_0 | Electric Field Strength in free-space |
| $E(d,t)$ | Electric Field Strength |
| E_g | Electric Field Strength (reflected ray) |
| E_{LOS} | Electric Field Strength (direct ray) |
| E_{TOT} | Total Electric Field Strength |
| f | Carrier Frequency |
| $F(v)$ | Fresnel's complex integrals |
| G_b | Gain Factor by transmitter antenna height |
| G_d | Diffraction Gain |
| G_r | Gain Factor by receiver antenna height |
| G_r | Receiver Gain |
| G_t | Transmitter Gain |
| h_r | Receiver Height |
| h_t | Transmitter Height |
| k | Constant related to the E_0 |
| P_r | Received Power |
| P_t | Transmitter Power |
| S | Shadowing Effect |
| t | Time |
| v | Fresnel-Kirchoff's Diffraction Parameter |
| γ | Propagation Losses Exponent |
| Γ | Reflection Coefficient |
| λ | Wavelength |
| π | Pi Number |
| ω | Angular Frequency |

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1 INTRODUCTION

1.1 Motivation and Justification

Nowadays, there is a constant increase of the vehicles on the roads and a high inter-connectivity among devices. Due to that, it is supposed a scenario where the cars communicate themselves each other, thereby creating an intelligent vehicles network that brings comfort to passengers and mainly assistance to drivers. The deployment of a vehicle network is called Intelligent Transportation Systems (ITS) and it can mainly serve to improve road safety and in motorways. For this purpose, the vehicles have to act like sensors and either transmit messages to other vehicles or to an infrastructure. The main goal is to support the drivers in quick detection of an abnormal situation and to help them avoid traffic jams and possible accidents. It would also be possible either to notify the speed limit from different roads or to report obstacles not previously reported or hidden, as well as accidents and potentially dangerous roads. According to United State Department of Transportation (USDOT, 2016), the connected vehicles are expected to reduce unimpaired vehicle crashes by 80%, while also reducing 4.8 billion hours that Americans spend in traffic annually.

But how to build a vehicular network? For that is suitable to define the Mobile Ad Hoc Networks (MANET), which is an interconnected group of mobile autonomous devices. Each device acts like a node that can receive and forward data. The devices can move themselves freely in any direction. Different from static network that needs an infrastructure like for example a router that addresses the data, the mobile network works without an infrastructure. In other words, each node is also a router that forwards the packets.

The route in a MANET is defined as the temporally establishment of a path since a source to a destination, without a centralized administration device. The path is defined by routing Ad hoc protocols by means of some rules that are deployed via algorithms.

That said, the vehicular Ad Hoc network (VANET) is a special type of MANET, in which the mobiles devices are composed by vehicles that establish connections with a vehicles (V2V) or with a roadside unit (RSU) well-called as Vehicle to Infrastructure (V2I).

Furthermore, some different types of VANET connections can be seen in academic works such as: Vehicle to Pedestrian (V2P) and Vehicle to Motorcycle (V2M).

The V2X and V2V communication have been considered as an important component inside the 5th Generation of mobile networks (5G), and at the same time, one of the most challenging applications of it, due to the specific features that the vehicular environmental demands. Furthermore, it demands ultra-reliable and low-latency communications for safety-critical use cases and has to supply high data rates in several scenarios.

Once these challenges are overcome, the vision of advanced driver assistance system, and, in an even longer perspective, complete autonomous driving cars promise not only less congested cities, less fatal accidents, but also a wide range of new business opportunities for a broad range of industries and benefits for the environmental.

All services and applications mentioned above based on VANETs must be tested properly in order to guarantee their availability and make it feasible in practice, otherwise instead of getting the traffic safer, it might cause fatalities. Due to the high costs and complexity to implement field tests that consider as many scenarios as possible, VANET's research relies heavily on computational simulations.

A framework, composed by a traffic simulator and a network simulator which establishes Wi-Fi connections between the traffic participants according to communication standards for vehicular network, is necessary to create this simulation environment. In order to simulate the movement of the vehicles was used the traffic simulator tool SUMO which works over a predefined map. The network simulation is provided by the Discrete Event Simulation Omnet++. Veins framework makes the connection between both so that information is swapped bi-directionally between SUMO and Omnet++. In addition, Veins contains the lower IEEE802.11p layers (PHY and MAC layers) that are an amendment to the IEEE 802.11 Wi-Fi reference in which some modification are introduced to enhance the behavior of the communicating nodes under such dynamic scenarios, thereby allowing exchange of data among vehicles.

However, some VANET's features are not supported on VEINS, such as Vehicle to X (V2X) communication, analysis of different sets of VANET applications and the European ETSI ITS-G5 stack itself over the lower layers (RIEBL, 2016). Artery framework is an ex-

tension of VEINS, and offers the possibility to register different implementations of vehicular applications like, for example, the Cooperative Awareness Message (CAM) or the Decentralized Environmental Notification Message (DENM) service. The last component is Vanetza, which performs the routing specific tasks inside the network simulation according to ETSI ITS-G5 stack.

This entire framework brings a problem when referred to the physical layer, once it is based on traditional radio propagation models. The signal propagation in vehicular environment has some particularities that differentiate from traditional ones and make it a challenge for being modeled. The main feature that distinguishes vehicular communications from others types of wireless communications are: The dynamic environment where the communications happen, since the radio propagation is strongly affected by the type of environment (most often qualitatively classified as rural, suburban areas and highways); Low antenna heights, resulting in frequent radio signal blockage; And at last, the vehicles' high mobility, which are in motion most part of the time, are affected by Doppler Shift Effect.

In the last few decades, dedicated wireless channels were specifically allocated to enable the development and implementation of vehicular communication systems. In order to guarantee that vehicular communications do not suffer from any type of interference from unlicensed devices, the Federal Communication Commission (FCC) in the United States and the European Conference of Postal and Telecommunications Administrations (CEPT) in Europe allocated a spectrum band at 5.9 GHz so-called Dedicated Short-Range Communication (DSRC) channel (KAKKASAGERI, 2014). This propagation is affected by some factors like absorption, refraction, reflection or diffraction of signal. In urban environment, many of these factors can be found due to the large amount of buildings and objects.

Wang et al. (2009) analyzed the state of the art in V2V channel measurement and modeling. Considering the approach that the environment can be modeled in a geometrically or non-geometrically manner and the distribution of objects in the environment in a stochastic or deterministic way, three main types of models were identified: non-geometrical stochastic models, geometry-based deterministic models, and geometry-based stochastic models;

The non-geometric stochastic models (e.g., free space, log-distance path loss (RAPPAPORT, 1996), etc.) are computationally efficient and easy to implement, however it does not take into account the surrounding vehicles. Cheng et al. (6) performed measurements of the V2V channel at 5.9 GHz frequency band and pointed out that vehicles as obstacles are the most probable cause for the difference in received signal power between the obtained experimental measurements and the dual slope piecewise linear channel model used in that study. On the other hand, the geometry-based models are highly realistic models, based on optical ray tracing (MAURER et. al., 2004). However, the realism of the model is reached at the expense of high computational complexity and location-specific modeling. Even with the recent advances in optimizing the execution of ray tracing models (MAURER et. al., 2004), the method remains computationally too expensive to be implemented in VANETs simulators.

In this context, the GEMV² radio propagation channel model was introduced, in order to fill the gap among accuracy, computational cost and scalability. GEMV² uses outlines of vehicles, building and foliage to assess their impact on the communication link. It can be considered as a mix between deterministic and stochastic models. The model was validated through an extensive field measurement at 5.9 GHz (BOBAN, 2014).

1.2 Objectives

This work targets the implementation of GEMV² (BOBAN,2014) geometry-based vehicle-to-vehicle radio propagation channel model into the Artery simulation framework for VANET applications, in order to simulate V2V communication in terms of received power and, at the same time, become the simulation framework more realistic.

The specific objectives of this dissertation are:

- Making a review of literature in relation to the following subjects:
 - Geometry-based Radio Propagation Models;
 - Traffic and Network Simulators;
 - VANET simulation framework – Artery;

- Customize and implement an urban map from UFPR campus and its traffic model to be used in traffic simulator.
 - Identify the research question and/or the research gap;
- Integrate the proposed channel model with the SUMO and Artery, in order to represent the vehicle performance metrics in the network simulator.
- Compare the obtained findings with traditional propagation models.

1.3 Structure of Dissertation

The dissertation's further sections are organized as follows: in Chapter 2 a theoretical foundation of the main items of the GEMV² and Artery based VANET communication in a top-down view are presented in more details. In Chapter 3 is characterized a methodology to implement the GEMV² into Artery framework and explained details about the implementation itself. In the Chapter 4 is introduced a simple methodology to validate the implementation. In Chapter 05 is made a comparison of the numerical results between GEMV² and traditional models over Luxembourg large scenario and over UFPR campus scenario. Finally, in Chapter 6, the conclusion and future work proposals are presented.

2 REVIEW OF THE LITERATURE

2.1 Introduction

As mentioned in previous section, the VANET depends above all on simulation frameworks that can represent the real environment as trustworthy as possible in terms of accuracy, scalability and functionalities as well as containing the architecture for vehicular communication according to local standards - WAVE for United States (WAVE, 2014) or ETSI ITS-G5 for Europe (ITS, 2010). To do so, it was used the framework detailed in Figure 2.1. Each item of it will be detailed hereafter.

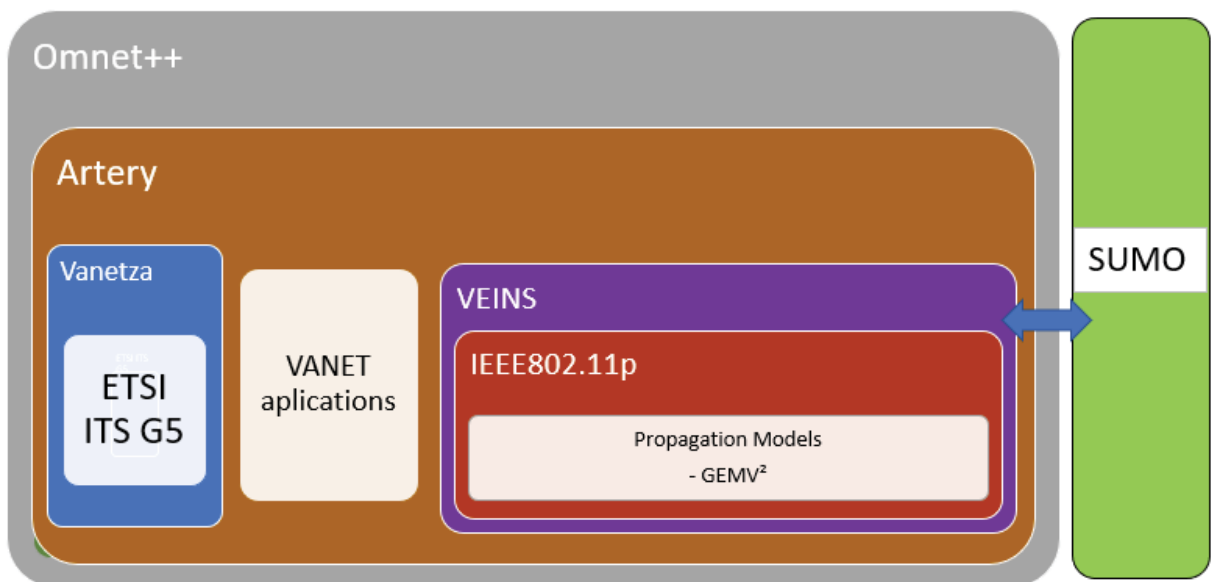


Figure 2.1: Framework to GEMV²-and-Artery based VANET communication.

The VANET simulation scenarios are directly linked to the modeling of radio channel transmission among the nodes. Therefore, it is necessary to know the exact positioning at each moment. Due to that, it is suitable the use of microscopic model on traffic simulator to model the vehicle's individual behavior and then analyzing the interaction in communication between them (ALVES et. al., 2009).

Initially, the mobility and network models were not created to interact with each other, which was essential feature for VANETs (CHOFFNES, 2005). There were some studies

in scientific community to develop specific mobility models for vehicular network considering aspects like simulation time, and complexity (KOLLER et al., 2012) (VIRIYASITAVAT et al., 2015).

2.2 Traffic Simulator - SUMO

The development of traffic simulator started for traffic engineering through the modeling of the highways' critics points and the urban intersections. The models were initially created to be analyzed by construction engineers and therefore, they were not meant for networks simulators. A significant characteristic to develop traffic simulators, and might even be a limitation, is the complexity of calibration. The realism level on transport planning is high and demands a large number of parameters, which have a determined influence on the answer. On the other hand, the vehicular communications networks developers do not demand high complexity, they only need the mobility path adapted to their needs.

Many simulators also have commercial license, which may result in a high financial investment in project. That is why, a large part of scientific community has started to work in open source simulators development.

The Simulation of Urban Mobility (SUMO) tool (KRAJZEWICK et al., 2012), allows a traffic simulation for large roads networks, and it is especially attractive for the vehicular study, since it is a highly portable and open-source software. SUMO includes both a console to insert the corresponding commands for the simulations executions as well as a graphic interface to visualize or interact with the traffic simulation output as shown in Figure 2.2.

The programming platform has been developed on C++ and the code finds itself in continuous development by German Aerospace Center Transport System (SUMO, 2015).

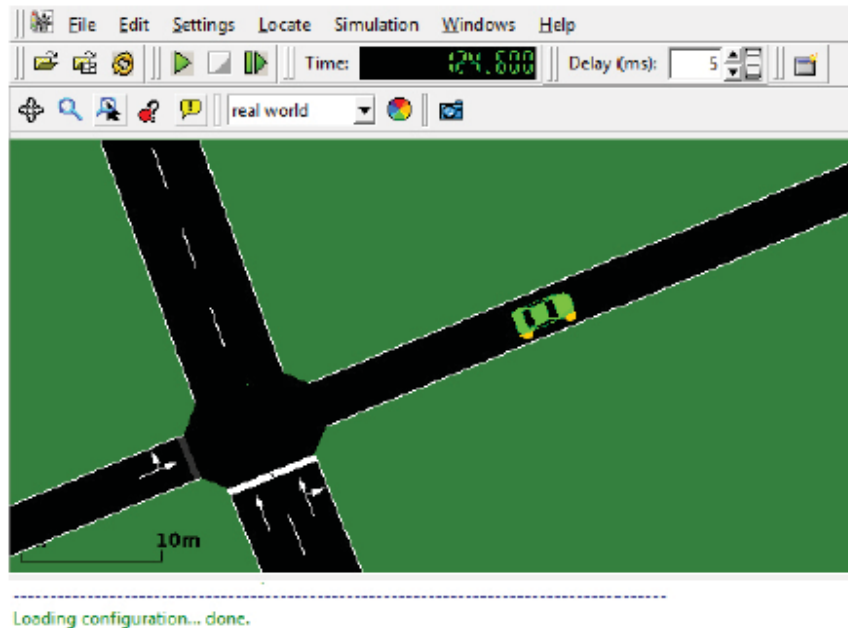


Figure 2.2: SUMO's Graphic interface.

The generation of the constants like routes, roads and the intersection distribution, can be elaborated manually to the users' needs, or it can be used real data. To import the geographic data several sources can be used like the VISSIM, the GIS ArcView or the OpenStreetMap (OSM) that are respectively a tool for traffic jam model, a geographic information system and free editable maps; Each one generates a file with different extension that can be imported to SUMO. These tools can be used in definition of topology, thereby configuring the scenario for performance evaluation.

The software can also generate output paths that might be inserted directly to some networks simulators like Omnet++, detailed in following section. On the other hand, there are different methods allowed in order to create traffic in SUMO: either it can create itself a completely random or manual origin-destiny route or it creates an optimal path through of some available algorithms like the Bellman-Ford (CORMEN et al., 2007).

The SUMO also allows to configure the models of macro and micro mobility. The macroscopic model describes large amounts of interest like a vehicular density and average speed. In this type of model, the important issue is the behavior of a sector or area and not of each individual vehicle. That is why, the simulation space is divided in sections, thereby decreasing the necessary computational resources in a more detailed

simulation. The microscopic model simulates the movement of each existing vehicle on scenario of the simulation, thus the simulator considers the motor features of each vehicles as well as the behavior of each driver. Due to high level of detailing for this model, the computational resources amount is high as well.

To detail the human micro-behavior in the vehicle is necessary to specify the car-following model (NAGEL et. al., 1992). This model allows describing driver's different behavior, for instance, it can determine the decreasing of velocity at the moment in which the driver is near of a change in vehicle direction. Another situation would be the driver decides to change lanes or not during his path, what would be subject the interactions with other vehicles or with its surroundings like the traffic lights or traffic jam. All this would produce different reactions, like passivity and aggressiveness, that are also implemented in model. The operation of this mechanism is intuitive and mainly consists in adapting the vehicle mobility as a series of rules to maximize the vehicle speed, but always trying to avoid a traffic accident.

Furthermore, some parameters allow approximating the SUMO's simulation to the reality, like for example, when the driver will decide to change of lane and overtake another vehicle. Due to which, the flexibility of configuration and a good interconnection with the network simulators, that the SUMO is rather requested for vehicular networks.

2.3 Network Simulator – Omnet++

Omnet++ is a modular, object oriented and discrete event simulator based on C++ (VARGA et al., 38). The operational model consists in hierarchical modules that communicate themselves each other through messages. Highlighting its free-source code, there is an effort from user community to develop both the simulation interface as well as the libraries and the simulations modules (like the IPv6, TCP, MANET, etc.). The program has two execution interfaces, one of them is a graphic environmental and another one is via console. The visual interface, shown in Figure 2.3, is a mainly didactic tool where can be visualized the packets interactions at each layer and that also enables the code debugging. The simulator can be executed in Windows, but it was developed in Linux-Unix.

The simulator uses the NED programming language as tool to model the topology of the network and the nodes. Thus, a router or an access point will be deployed by different modules, ensuring a liberty to modify each module with almost total independence. Therefore, a model is built by hierarchic modules. Each module can contain complex framework of data with its own personalized parameters.

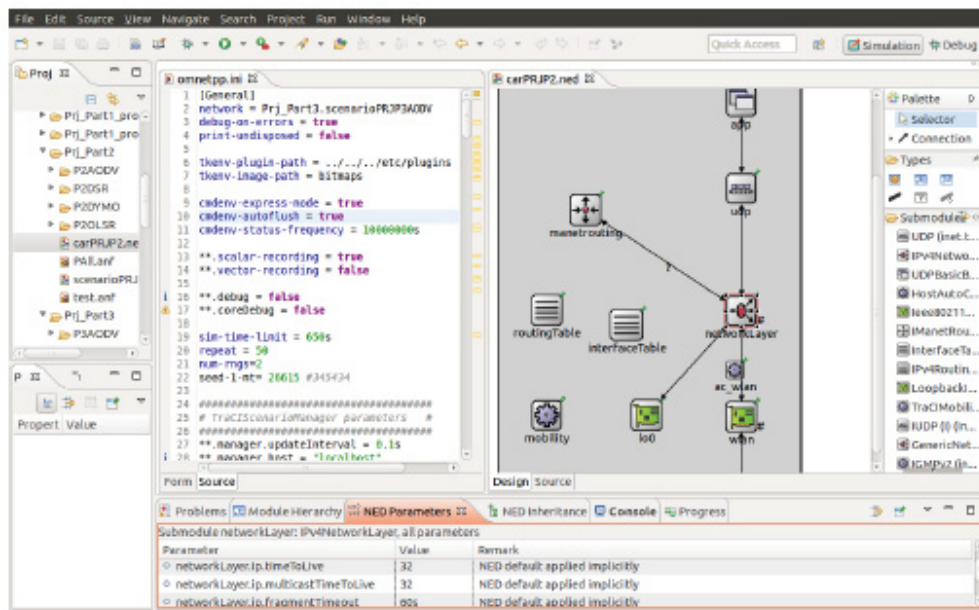


Figure 2.3: OMNET++'s graphic interface.

Basically, the NED language can define simple, complex and network modules. The last one contains the components and specifications of a communication network as well as the number of nodes or the physical distribution of base station. To facilitate the creation of the code, especially for network module, it can work itself with the graphical editor (GNED). This editor allows creating, programming and configuring the network elements without using the language directly, it is only necessary to perform a drawing with elements' representative icons and it is the GNED that will generate the code lines automatically which will be available for the users.

The events occur inside of simple modules, which are implemented in C++ using the Omnet-classes library. Inside these modules, the algorithms and properties of complex modules start or finalize in each state change. Once all modules have been elaborated

and configured, it will be necessary the file creation “.ini” that will allow the start of simulation. In this file is described both the own parameters of the simulation as well as the number of interactions, the duration time or the values of the attributes of the simple modules or the entire topology of the network model.

2.4 VEINS

The Vehicles in Networks Simulations (VEINS) tool (SOMMER, 2016) is a framework for vehicular network simulation. It facilitates the bidirectional interaction among the SUMO and Omnet++ simulators, that are based on events, what it means that the elements movements on the simulation will be restricted in periodic-time intervals. When an execution-time synchronization point is reached between both simulators, the interconnection is completed and thus, both can be connected bidirectionally. A communication interface called TraCi, which is implemented over a socket (TCP), allows that the simulation is sequential and fed back in both simulators.

The TraCi's role is to provide a communication medium between the Omnet++ and SUMO. The architecture for that is the client-server, where the client (Omnet++) will send commands to server (SUMO) to control the simulations state. The basic operation mode consists of storing in a row all commands that get among the simulation periods to after being forwarded and executed, thereby ensuring the synchronous execution. At a unit of determined time, the Omnet++ will send the stored commands to the SUMO, so that it completes the simulation with the information that it is being executed. Once this state is over, SUMO will send as answer a series of commands and the location of all vehicles. When the network simulator receives these information, it will be able to establish the nodes movement. After that, it will execute the next step of simulation, where the nodes will react it depending on the new mobility condition, what it will generate new commands that will once again be sent to SUMO, thus the process is repeated until completing the simulation.

Finally, Veins makes use of INET framework, that is a model packet for communication networks to be used on Omnet++. INET is considered the standard protocols models libraries, containing models for the internet stack (TCP, UDP, IPv4, etc.), wireless and

wired link layer and physical protocols (PPP, IEEE 802.11p, etc.) as well as MANET mobility protocols. However, some VANET applications and features contained in ETSI ITS-G5 are not supported on VEINS.

2.5 ETSI ITS G5

An intelligent transportation system (ITS) is an advanced application which, without incorporating intelligence as such, targets to proportion innovative services regarding different modes of transport and traffic management and enable users to be better informed and make safer, smarter and more coordinated use of transport networks.

ETSI ITS-G5 is a European protocol stack to enable ITS applications. It was defined in 2004, and has undergone a thorough standardization process. This included extensive field testing (starting in 2008 with the German simTD field tests with 400 vehicles (KOLLER et al., 2012)) and multi-vendor interoperability testing (ETSI plugtests, 2011). The ETSI ITS-G5 protocol set is detailed in Figure 2.4, which also serves as base for Artery's architecture that will be introduced on following section.

The network and transport protocols are based on GeoNetworking protocol (ITS, 2013), which is responsible for routing VANET packets, and Basic Transport Protocol (BTP) (ITS, 2013). Both are used to find a path in the network. The Facilities layer provides application support and connects the protocol stack to the vehicle-internal bus systems. The cross-functional Management and Security layers are intended to maintain system-wide parameters and protect V2X communication from external attacks respectively.

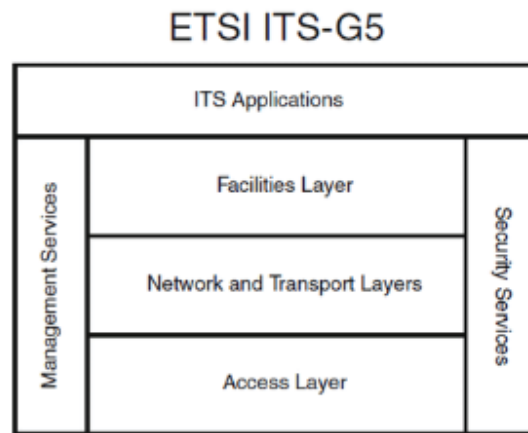


Figure 2.4: ETSI ITS-G5 reference architecture (ITS,2010).

The IEEE 802.11p standard, which specifies the physical and MAC layers (access layer) for vehicular applications, has been used both for the WAVE and ETSI-ITS G5 architecture. For upper layers, the ETSI-ITS G5 has developed their own protocols (MAURER et. al., 2004). Those vehicular standards and their respective layers are highlighted in Figure 2.5.

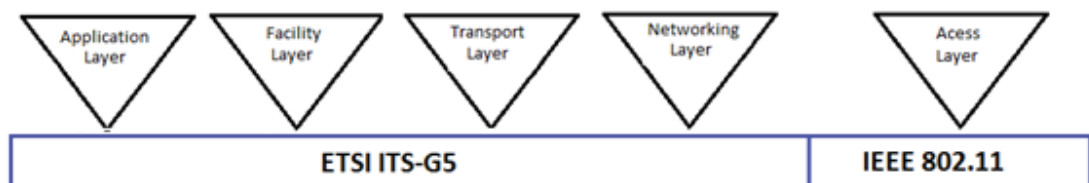


Figure 2.5: European VANET's communication architecture.

2.6 Vanetza

Vanetza (RIEBL, 2015) is an open source standalone implementation of some major ITS-G5 components (ITS, 2013). The main idea behind of Vanetza was the simulation of hundreds to thousand vehicles interconnected by using the ETSI ITS-G5 implementation, first operating together with VEINS and then with Artery, detailed in the next section (RIEBL, 2015). The ITS-G5's main components implemented by Vanetza are congestion

control, security-cross-layers, GeoNetworking and Basic Transport protocols which are colored in grey in Figure 2.6.

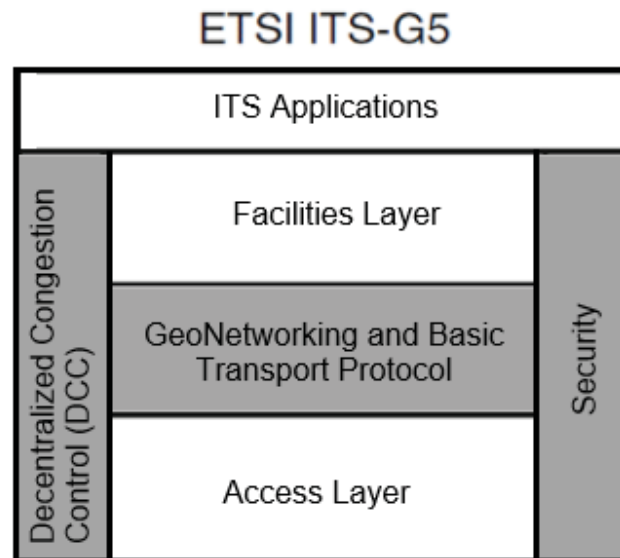


Figure 2.6: Layers supported by Vanetza (grey) in the ITS-G5 architecture.

GeoNetworking (ITS, 2014) is used to route VANET packets due to its fast-changing network topology. Therefore, geographic routing is much more effective because its algorithms do not depend on the network topology. GeoNetworking provides many features, e.g. routing of packets based on geographic positions and areas, detection of duplicate packets, store & carry forwarding for delay-tolerant transmissions, and packet repetitions (ITS, 2013).

The BTP (ITS, 2014) provides an optimized transport service in the VANETs. Its main goal is the multiplexing of messages from different processes at the ITS Facilities layer, e.g. CAM and DEN services, for the transmission of packets via the GeoNetworking protocol as well as the de-multiplexing at the destination (ITS, 2014).

Cross layers Security depend upon trustworthy data transmitted by other vehicles and the infrastructure. It brings privacy protection mechanisms for users and drivers. Vanetza owns `geonet::Router`, that automatically put in a security envelope all data requests from upper layers. When a signed packet is received, the signature and the corresponding certificate are checked for validity (RIEBL, 2015).

Cross layer Decentralized Congestion Control (DCC) provides stability in the ad-hoc network by providing resource management when there are a high number of C-ITS messages in order to avoid interference and degradation of C-ITS applications (ITS, 2013).

DCC_acc acts as gatekeeper above the access layer, i.e. it enforces minimum time intervals between outgoing packets of each priority class. DCC_fac adapts the message generation rate, so no packets are delayed or dropped by DCC_acc. DCC_net – whose implementation is currently work in progress – is supposed to share Channel Busy Ratio (CBR) measurements among neighboring nodes (RIEBL, page 3, 2015).

2.7 Artery

Artery is a simulation framework that allows an interface to application layer for VANET applications. If referred to ETSI ITS-G5 reference architecture depicted in Figure 2.4, it would represent the facilities and application layers. Artery allows that application layer registers various applications by creating Omnet++ modules (RIEBL, 2015).

Artery is an extension of Veins framework since it adds to this one the European VANET communication features. Furthermore, it also comprehends INET framework as an option to wireless link and PHY layers protocols and supports LTE cellular communication (ITS, 2013) as well as sensors attached to vehicles for environmental perception [ITS, 2014], (XU and SAADAWI, 2001).

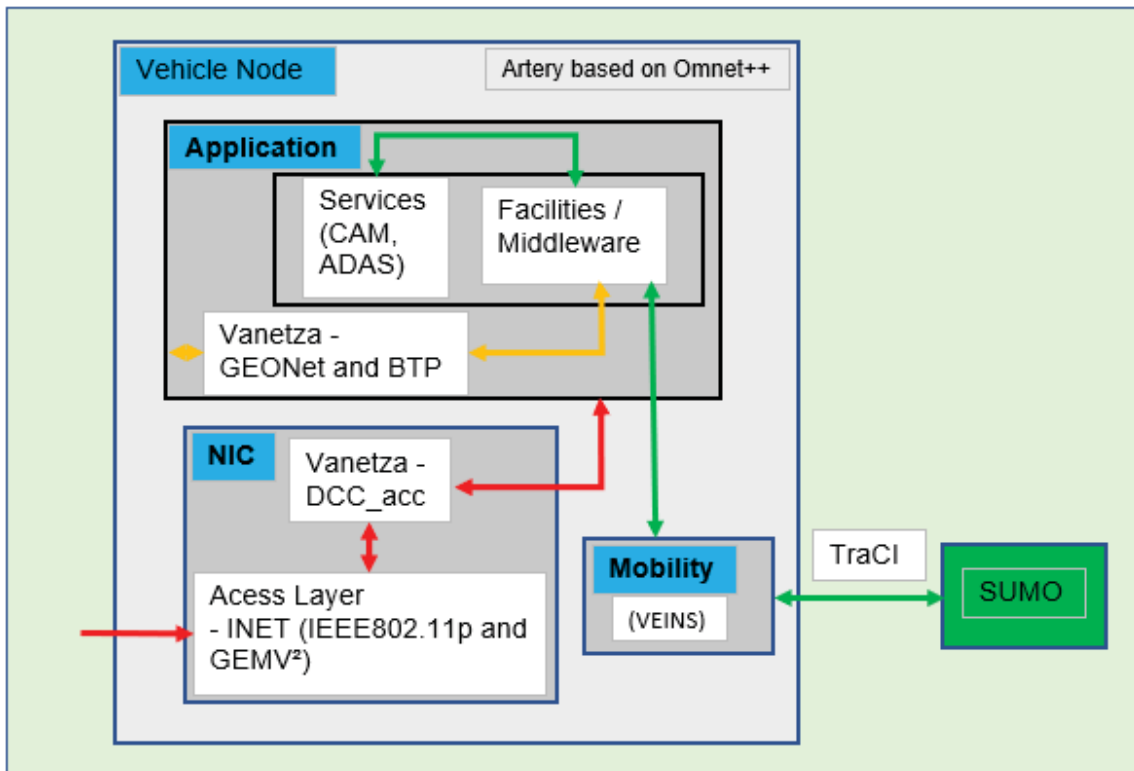


Figure 2.7: Structure of a vehicle node in the Artery framework. Adapted from (OBERMAIER, 2017).

A vehicular node based on Artery framework is basically composed of three modules as detailed in Figure 2.7. The Network Interface Card (NIC) which is composed of access module (PHY and MAC layers) and a part of Vanetza (DCC_acc) module, the application module and the mobility module.

The access module simulates the physical transmission media among vehicles nodes. Therefore, it checks whether a frame can be physically delivered at the addressed receiver or not by applying radio propagation models. If a frame is not thrown away, it is forwarded to the MAC layer, which performs actions according to the IEEE80211.p protocol. This includes activities related to channel management such as messages queueing according to their priority. In addition, the NIC module contains the DCC_acc, which is responsible for controlling time intervals between outgoing packets.

The application module contains the services and facilities/middleware which are the main Artery's modules and the routing layers of the ETSI ITS G5 specification (GeoNetworking, BTP and DCC) implemented by Vanetza. The ITS-G5 middleware is the Artery's major element, which acts like an information hub and routing provider to all services. The services are the applications themselves like standardized messages (ITS, 2014) such as the DENM and CAM as well as ADAS functionality. Those services can either send or request messages through Artery's middleware. Every service registered to the application layer is updated on each simulation step performed by Omnet++ (RIEBL, 2015). The routing layers are responsible for handling packets from or to middleware regarding traffic class, transport type, destination port, etc, as specified by BTP and GeoNetworking protocols. Each vehicle provides its own router, which is responsible for addressing other vehicles and geographic areas (RIEBL, 2015).

Still part of the application module, Artery provides a facility member so that the services can interact with the VEINS' mobility module to retrieve data related to the movement of a vehicle, for example the speed and the position of a vehicle.

2.7.1 Message Flow - Receiving a message

The incoming message flow inside a vehicle node is marked by red arrows in Figure 2.7. If a message is received by the physical layer, a defined, so-called decider calculates whether a frame can be received without error. If no error is detected, and therefore the frame is not thrown away, it will be handled up to the MAC layer. After passing the MAC layer the message will be processed by the router located in the application module of the vehicle node. The router is responsible of deciding if a packet should be processed by its own vehicles application layer, or if the packet must be forwarded to another node. If the router is a valid receiver of the packet, the packet is passed to an application according to its port number (OBERMAIER, page 23-24, 2017).

2.7.2 Message Flow - Sending a message

If a service triggers the sending of a message, the data Packet Data Unit (PDU) generated by this service is passed into the router. Like in a usual wired network, the router is responsible for determining the next hop of a packet. According to the used routing mode a specific next hop or various receivers are addressed. After adding of the routing information to the packet, it is passed down to the MAC layer. As soon as the sending request is received by the MAC layer, it will be queued into the output queue according to the priority of the packet. In case of a higher number of message, the Distributed Congestion Control (DCC) algorithms can drop the packets in order to provide stability (OBERMAIER, page 23-24, 2017).

2.7.3 Data Flow

The data flow is specified by green arrows in Figure 2.7. The information according to the last simulation step is received over the TraCI connection (SOMMER, 2016). This information is stored and processed inside the facilities submodule. This allows to calculate data, requiring more than one simulation step to obtain. For example, this can be the curvature or the yaw rate. All applications and services registered in the application module can access information from the facilities module when needed. For example, a CA service needs to know, among others, the position and the speed of its vehicle to generate CA messages with appropriate data (ITS, 2014) (OBERMAIER, page 23-24, 2017).

2.8 IEEE802.11p Standard

The physical and medium access control layers of the two main protocol stacks for vehicular communications systems rely on the IEEE802.11p standard.

In comparison with the typical Wi-Fi operation (802.11 Part 11, 2012), the American Society for Testing and Material (ASTM) has done a number of modifications in order to enhance the behavior of the communicating nodes under such dynamic scenarios. For instance, the channel bandwidth is reduced from 20 MHz to 10 MHz, in order to mitigate

the effects of multi-path propagation and Doppler shift. As a consequence, the data rate is half of what can be obtained with standard Wi-Fi, i.e., from 3 Mbit/s to 27 Mbit/s instead of 6–54 Mbit/s (ITS, 2011).

In order to guarantee that vehicular communications do not suffer from any type of interference from unlicensed devices, the Federal Communications Commission (FCC) in the United States and the European Conference of Postal and Telecommunications Administrations (CEPT) in Europe, allocated a dedicated spectrum band at 5.9 GHz so-called Dedicated Short-Range Communication (DSRC). The frequency range, located in DSRC band, covers from 5.86 GHz till 5.92 GHz. So, 7 channels of 10 MHz are used, where one of them is for control, two of them are for future use and the other ones are used for different services as shown in Figure 2.8. Moreover, it is mandatory in Europe to have two radios in each vehicular communication platform, in order to guarantee at least one radio always tuned in the dedicated safety channel (ITS, 2011).

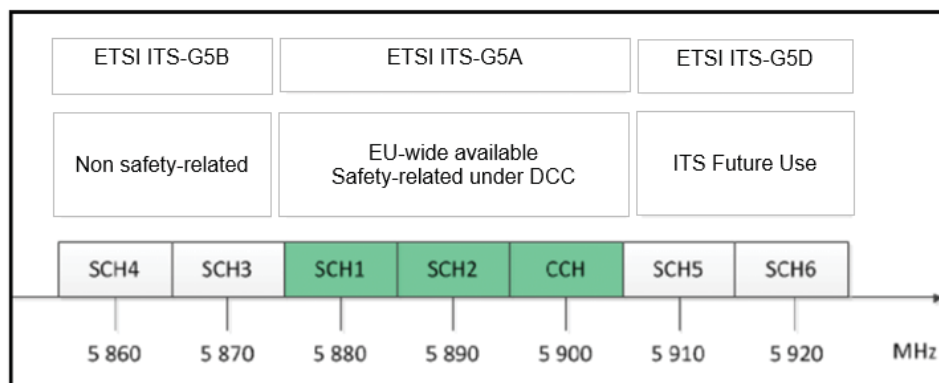


Figure 2.8: Spectrum allocation for vehicular communication (CAMPOLO and MOLINARO, 2013).

The radio-propagation model provides information about limitations on the wireless communications systems performance.

The radio-propagation channels have one of the most complex mathematical models in a wireless communication system, according to the state-of-the-art study presented in (VIRIYASITAVAT et. al., 2015), which compares the main radio propagation models regarding the: spatial and temporal dependency; extensibility to different environments; applicability; scalability; temporal variance and non-stationary; antenna configuration; The

GEMV² model fulfilled all properties presented above, except the antenna configuration. It is presented as an efficient model for realistic large-scale simulation with thousands of communicating vehicles in various vehicular environments (urban, rural, highway). In addition, it allows the analysis of networking related metrics, such as packet delivery rates, effective transmission range, and neighborhood size (VIRIYASITAVAT et. al., 2015).

One guideline for choosing a suitable radio propagation model is presented in (VIRIYASITAVAT et. al., 2015). The type of application (network topology statistics, safety-critical applications, system-wide performance analysis) and availability of the required data (either geographical or measurements, system-wide performance analysis).

2.8.1 GEMV²

The Geometry-based Efficient Propagation Model for V2V communication (GEMV²) (BOBAN, 2014) is a wireless propagation channel model specifically for vehicular environment with the goal of predicting the propagation losses in vehicle-to-vehicle communication. It incorporates the following propagation: 1) diffraction, 2) reflection, and 3) scattering.

Diffraction is the phenomenon liable for explaining the existence of electromagnetic fields at non-visibility regions caused by obstacles, known as shadowing regions. Such obstacles encountered by the electromagnetic waves can be natural or artificial in the urban, suburban or rural environment. Mathematically, the calculation for evaluating the attenuation by diffraction is complex, making itself necessary the use of the mathematical formulation based on geometric, it called Geometric Theory of Diffraction (GTD) and its extension for the Uniform Theory of Diffraction (UTD) (SILVA, 2004).

Reflection is the phenomenon that occurs when the electromagnetic wave hit on a surface that separates two environments, with dimensions much larger than the wavelength that it propagates. Part of the energy from this wave is reflected, and the other part is transmitted, penetrating the other medium. The corresponding parcels to the transmitted and reflected energies are calculated by the transmission and reflection coefficients respectively. The transmission and reflection coefficients depend on electrical and magnetic permeability and medium conductivity in which the electromagnetic wave

propagates itself. Moreover, the frequency and the incidence angle on the medium in question also bias the respectively coefficient. For the analysis of this phenomenon is used the theory of geometric-optics rays.

The scattering occurs when the propagation medium is constituted with small dimensions objects (rough surfaces, small objects), in relation to the wavelength (PEREIRA, 2007).

Besides that, GEMV² uses outlines of vehicles, buildings, and foliage to distinguish into three different types of links: line of sight (LOS), non-LOS (NLOS) due to vehicles, and NLOS due to static objects as seen in Figure 2.9. Such distinctions are made through of an analyze of first Fresnel ellipsoid. Whether one or more object between the communication pair intersect the ellipsoid corresponding to 40% of the radius of the first Fresnel zone, the channel is considered NLOS.

For each link, GEMV² calculates the large-scale signal variations deterministically, whereas the small-scale signal variations are calculated stochastically based on the number and size of surrounding objects.

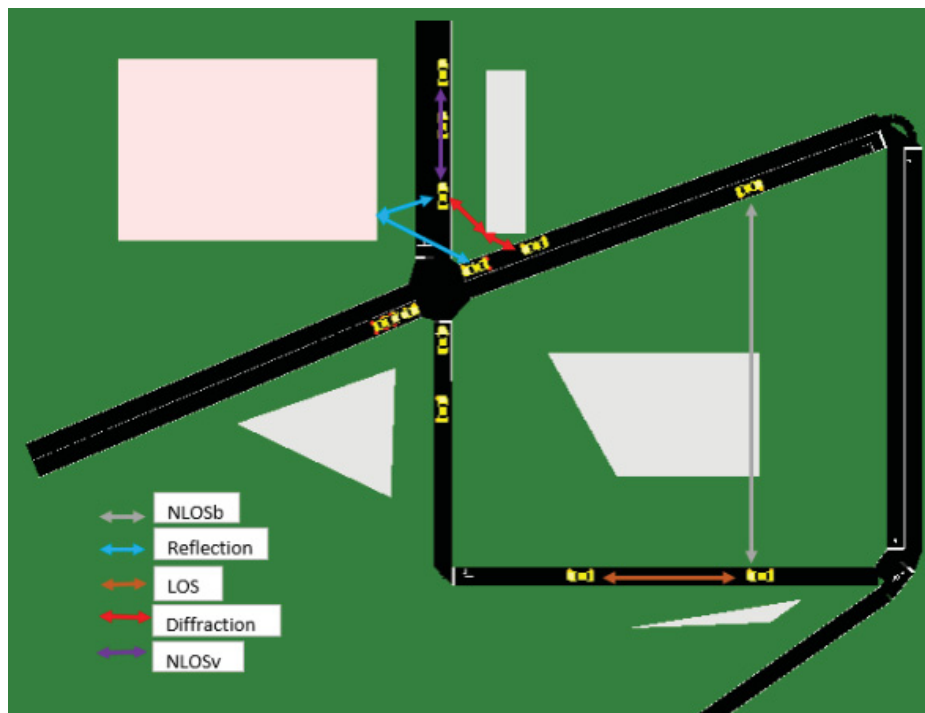


Figure 2.9: GEMV² link types.

In order to check which objects influence both large-scale and small-scale signal variation, an analyze is done through ellipse-bound area. The transmitter and receiver cars are placed on ellipse's focus whose major axis is equal to the link communication range (obtained by field measurements – 500, 400 and 300 meters for LOS, NLOSv and NLOSb respectively), thereby generating the search area as shown in Figure 2.10. The vehicles are colored of black and the buildings of light-brown.

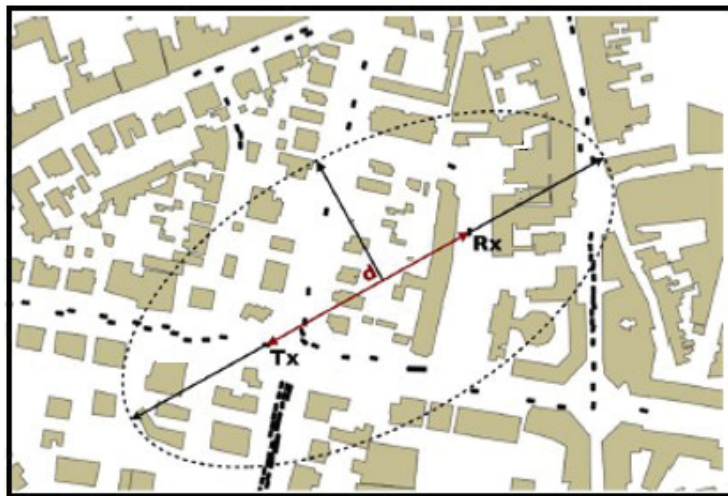


Figure 2.10: GEMV²'s Ellipse-bound area. Adapted from (BOBAN, 2014).

The modeling of the large-scale signal variations is made according to the link types: Upon LOS link type, two-ray reflection model.

The two-ray ground reflection model, shown in Figure 2.11, is based on geometric optics. It considers a direct and reflected path on ground between the transmitter and the receiver. This model was reasonably considered accurate to predict the signal strength in large scale (RAPPAPORT, 2000).

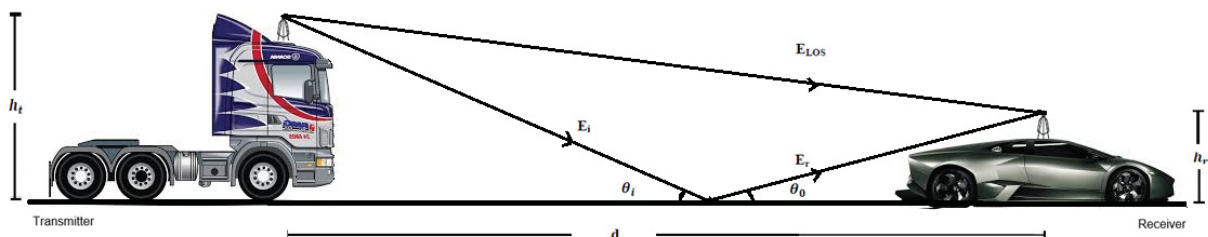


Figure 2.11: Two ray ground reflection model

The concept of calculation of signal electric field strength, by applying two-ray method, is given by (SIZENANDO, 2006):

$$E(d,t) = \frac{E_0 d_0}{d} \cos(\omega_c(t - \frac{d}{c})) \quad (1)$$

where E_0 is the electric field strength in free-space (V/m) (RAPPAPORT, 2000), d_0 is the arbitrary referential distance from transmitter (m), often 1m, $\frac{(E_0 d_0)}{d}$ represents the electric field module ($E(d, t)$) at a distance d (m) from transmitter, t represents the time (s), ω_c is the carrier frequency (rad/s) and c is the light speed (m/s).

The expressions of electric field strength from the direct and reflected ray are respectively:

$$E_{LOS}(d_{LOS}, t) = \frac{E_0 d_0}{d'} \cos(\omega_c(t - \frac{d_{LOS}}{c})) \quad (2)$$

$$E_r(d_{i+r}, t) = \Gamma \frac{E_0 d_0}{d''} \cos(\omega_c(t - \frac{(d_i + d_r)}{c})) \quad (3)$$

Where Γ is the reflection coefficient for the soil, which was taken empirically ($\Gamma = -1$ for the case where there is perfect reflection). The total electric field strength E_{TOT} , at receiver, will be the vector sum of the direct and reflected component.

$$|E_{TOT}| = |E_{LOS}| + |E_r| \quad (4)$$

Using the geometric optics from the image method illustrated in Figure 2.12, and evolving the expression of total field strength as well as the simplifications from the angular considerations, it is obtained:

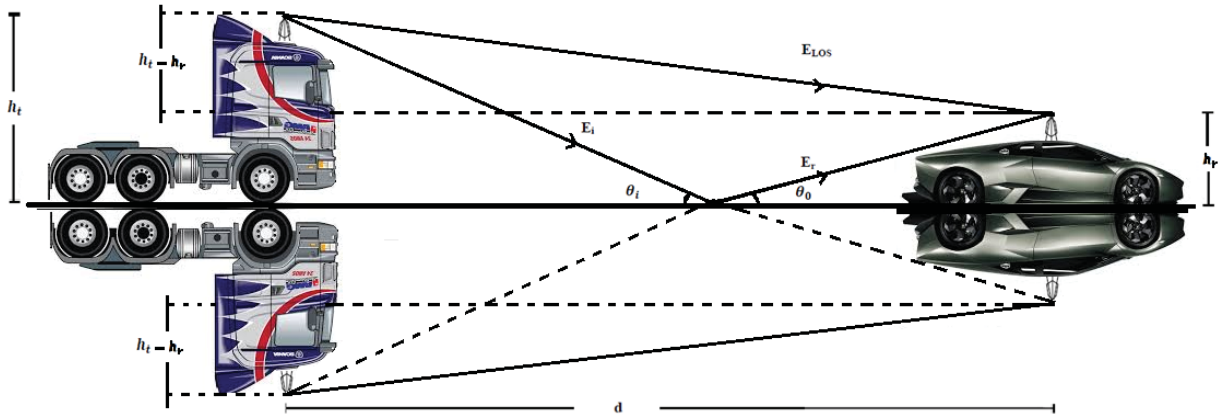


Figure 2.12: Mirror method simplification.

$$E_{\text{TOT}}(d) = \frac{2E_0 D_0}{d} \frac{2\pi h_t h_r}{\lambda d} \approx \frac{k}{d^2} \quad (5)$$

where, k is a constant related to: E_0 ; transmitter and receiver's antennas height; wave length λ (m).

Upon NLOS link type caused by vehicle (NLOS_v) (BOBAN, 2011), a multiple knife-edge model is used to calculate the losses due to the diffraction over both vehicles and buildings. The multiple knife-edge is an extension of the single knife-edge whenever there is more than one hurdle.

In order to estimate the losses caused by an obstacle, the single knife-edge model idealizes that the obstacle have either a knife-edge form of negligible thickness or a thick smooth form with a well-defined radius of curvature at the top. To do so, all the geometrical parameters are combined together in a single dimensionless parameter denoted by v and the wavelength must be fairly small in relation to the size of the obstacles ($f > 30$ MHz) (ITU-R, 2007).

$$v = h \sqrt{\frac{2}{\lambda} \left(\frac{1}{d_1} + \frac{1}{d_2} \right)} = \frac{h\sqrt{2}}{\sqrt{\frac{\lambda d_1 d_2}{d}}} \quad (6)$$

Where h is the height of the top of the obstacle above the straight line joining the two ends of the path. If the height is below this line, h is negative. d_1 and d_2 are distances of

the two ends of the path from the top of the obstacle respectively and d is the length of the path.

Through approximation of Fresnel-Kirchhoff loss given by ITU-R P.526, equation 31, for v greater than $-0,78$ the losses are in dB (ITU-R, 2007):

$$J(v)=6.9+20\log\sqrt{((v-0.1)^2+1)+v-0.1} \quad (7)$$

However, if there are more than one hurdle, some strategies are used in order to classify the hurdles into primary and secondary according to their impact over the line of sight and afterwards, applying the single knife-edge model among the primary iteratively and then among secondary. In addition, a correction term is needed to consider for spreading loss due to diffraction over successive obstacles. Exemplifying the idea above, in Figure 2.13 is shown some obstacles' profiles between the transmitter (T) and receiver (R), on which are identified the primary (P) and secondary (S) obstacles. These procedures are contained in ITU-R P.526.

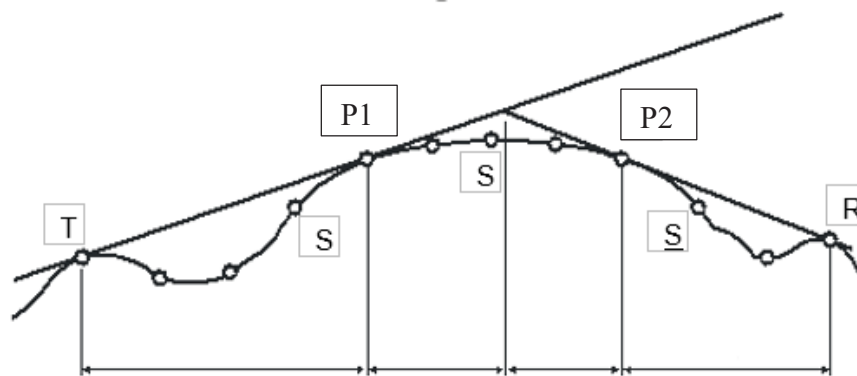


Figure 2.13: Multiple obstacles (ITU-R, 2007).

According to ITU-R P.526, the total diffraction loss, in dB, may be written:

$$L_d = \sum_{p=1}^N L_P + \sum_{s=1}^M L_S - 20 \log C_N \quad (8)$$

where: N and M is the number of primary and secondary respectively, L_P is the diffraction loss for the section of the path between primary hurdles, L_S is the diffraction loss for the section of the path between secondary hurdles. For instance, the calculus for considering the first primary ($L_{P=1}$) would be to apply equation 6 and 7 over T-P1-P2 (Tx-Obstacle-Rx).

$$CN = (P_a / P_b)^{0.5} \quad (9)$$

is the correction factor, which in turn, depends on the distances between the hurdle and the transmitter (s_1) and receive (s_2) according to the equations 10 and 11 (ITU-R, 2007).

$$P_a = s_1 \prod_{p=1}^N [(s_2)_i] \left(s_1 + \sum_{s=1}^M [(s_2)_j] \right) \quad (10)$$

$$P_b = (s_1)_1 (s_2)_N \prod_{i=1}^N [(s_1)_i + (s_2)_i] \quad (11)$$

Upon NLOSv, it is considered the diffraction loss from both sides of the vehicles and from vehicle's roof.

Last but not least, upon NLOS link type caused by buildings (NLOSb), there are two ways for modeling: The simplest way is to apply the log-distance path loss model (RAP-PAPORT, 2000) which considers that the received mean power decreases logarithmically in relation to distance from the transmitter. This model is featured by equation 12:

$$PL(d) = PL(d_o) + 10n \log\left(\frac{d}{d_o}\right) \quad (12)$$

Where n represents the path loss exponent which was obtained empirically, $PL(d_o)$ is the pathloss considering the free-space model (RAPPAPORT, 2000) at a reference distance d_o , and d is the separation between transmitter and receiver. This model does not depend on neither frequency nor gains from transmitter and receiver antennas.

The hardest and second method considers the diffraction and reflection effects but only to single-interaction (single-bounce) rays. One exception would be the multiple diffraction due to vehicles, however if there is a NLOS link type due to both vehicle and building, the GEMV² only considers the NLOS_b, since the attenuation is much bigger in NLOS_b than in NLOS_v.

The diffraction loss is similar to diffraction over the vehicles in case of NLOS_b link type, the multiple knife-edge is used, however, over buildings are only considered for the horizontal plane, since the buildings are too tall for diffraction over the rooftops.

As for reflection effect, over vehicles' roof for this sort of link is not regarded due to an effort to keep the GEMV²'s low computational complexity. Besides that, it is worth reminding that the vehicles' sides will only be a reflector potential, if the vehicle has height taller than both communicating vehicles' antennas. Regarding the reflection off buildings always is possible, once they are significantly taller than any vehicles.

The small-scale fading is caused by multipath and shadowing. The multipath effect is characterized as being the composition of the transmitted signal's original versions that travels in different ways. The shadowing manifests itself by signal level fluctuation with the distance caused by surrounding obstacles (SIZENANDO, 2006). It is usually modeled by a random variable with a certain probability distribution. On GEMV² was adjusted the collected data in field tests with the zero-mean normal distribution $N(0, \sigma)$ (GRINSTEAD and SNELL, 1998). The variation due to the different link types is reached by simple modeling of the standard deviation, which is proportional to the number of vehicles (NV_i) and the area of buildings and foliage (AS_i) around the communicating pair by ellipse-bound area. The equation for the standard deviation according to (BOBAN, 2014)

$$\sigma = \sigma_{\min} + \frac{\sigma_{\max} - \sigma_{\min}}{2} \left(\sqrt{\frac{NV_i}{NV_{\max}}} + \sqrt{\frac{AS_i}{AS_{\max}}} \right) \quad (13)$$

where NV_{\max} and AS_{\max} are the maximum number of vehicles and building and foliage from historical data and geographical database respectively. The minimum and maximum values of the small-scale signal deviation obtained empirically for each link type by (BOBAN, 2014) are shown in Table 2.1.

Table 2.1: Minimum and Maximum values of the small-scale signal deviation
(BOBAN, 2014)

| Link Type | σ_{min} | σ_{max} |
|------------------|---------------------------------------------------|----------------|
| LOS | 3.3 dB | 5.2 dB |
| NLOSb | 3.8 dB | 5.3 dB |
| NLOSv | 0 dB (refl&diff) /4.1 dB (MANGEL et al., 2011) | 6.8 dB |

3 IMPLEMENTATION AND VALIDATION

3.1 Methodology of Implementation

The methodology of implementation of the GEMV² propagation model into Artery simulation framework was developed according to the flowchart shown in Figure 3.1. It is important to emphasize that differently of the GEMV²'s output on MATLAB, the system's output for this implementation is in function of an attenuation (A) that will be explained later, and not in terms of the received power. This occurs in order to fit the output according to the metrics already implemented on Omnet++ and at INET framework, which were taken as base.

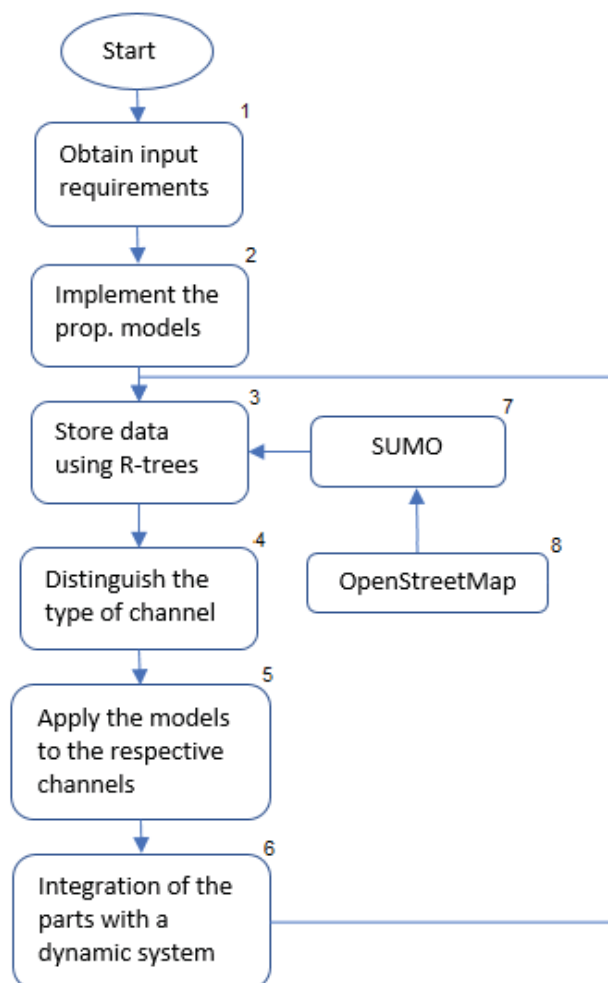


Figure 3.1: Flowchart of implementation.

In order to implement the flowchart above, an UML diagram with flowchart's all requirements has been created as seen in Figure 3.2. The input parameters (transmission power, frequency, antenna gains and communicating pair) and the map based traffic model are not part of the module. The input parameters are adjusted at INET module, except the communicating pair, that is set according to the application layer demand (Artery's service). The traffic model comes from SUMO and will be mentioned later.

The PathLoss is the central class. It mainly depends on the Link Classifier class once it will say which type of channel is the current communication. It makes use of the Small Scale Variation, NLOSb, NLOSv and LOS classes to get information about the small and large-scale values. Finally, it combines properly the values and return the final value. The returned value refers to the attenuation (A) as already was mentioned above. The correlation between the pathloss (PL) and this attenuation is demonstrated in equation 15.

$$P_r = P_t G_t G_r A \quad (14)$$

The equation 14 shows the way that the INET module computes the received power. The transmitter power (P_t) and the antenna gains (G) are known in advance and therefore, our system's output must be A.

When compared the equation 14 to the traditional received power equation (RAPPAPORT, 1996), we get the relationship between the attenuation (A) and the path loss (PL) as seen in equation 14.

$$A = \frac{1}{PL} \quad (15)$$

The Vehicle Index and Obstacle Index are classes responsible for collecting, storing and handling vehicle and obstacle's data. Basically, they obtain the vehicle and obstacle's data like outline's position, area value and centroid position from SUMO in real time through Traci interface. After that, the data are stored in R-tree structures in order to accelerate searching for objects in space. It was used the rstar as node splitting algorithm, once it has demonstrated a good querying and building performance. Last but not least, there are member functions that are responsible for mounting the communication ellipse

as already was explained its functionality above and for verifying whether there is anything intercepting the line of sight between two points.

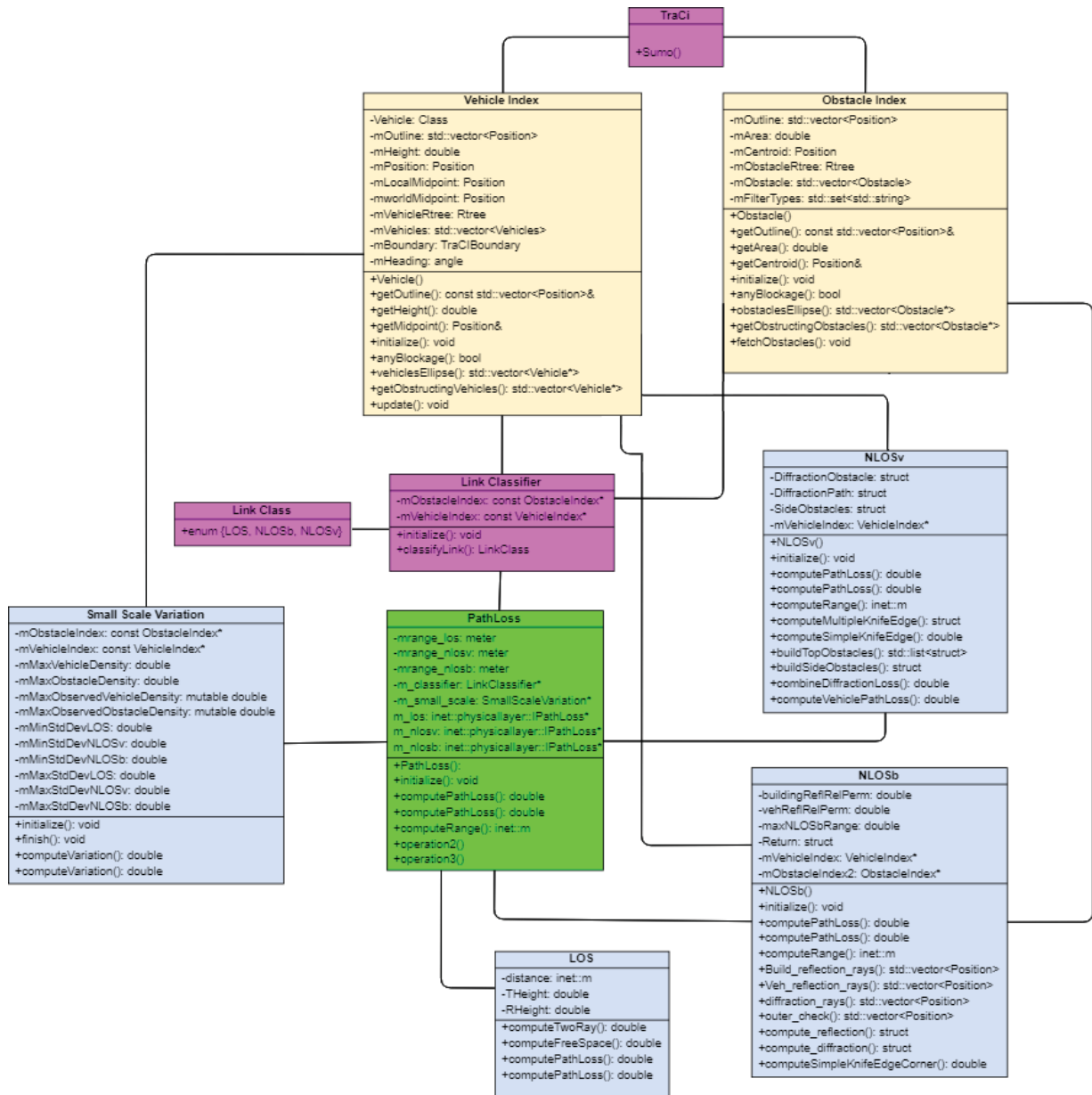


Figure 3.2: GEMV2's UML diagram on Omnet++.

The Link Classifier is a class designed for classifying which channel is present in the given time frame. Basically, it just uses the member function created in the Obstacle Index

and Vehicle Obstacle classes that checks intercepting objects between two points, so that it is able to classify the communication channel in: LOS, NLOSv and NLOSb.

The remaining classes (LOS, NLOSv, NLOSb, Small Scale Variation) implement the radio propagation model itself. To do so, it uses some objects from Obstacle Index and Vehicle Obstacle classes in order to get information about the variables demanded on the models.

Doing a comparison between the GEMV² source code on MATLAB and on Omnet++, which has been implemented on this dissertation, observes an optimization on the source code of more than 50 functions on MATLAB to only 8 classes on omnet++, without mentioning the lines of code. Part of it, it is related to the use of object oriented programming c++ itself and also the use of some boost libraries.

3.2 Methodology of Validation

In order to validate the implementation, some simple tests have been created some simple tests scenarios on SUMO manually for each link type, so that it was able to analyze the key variables of the applied models for each link type. Afterwards, it has been done a comparison between the values obtained from Sumo and MATLAB over those created scenarios. An extern manipulation in the result from omnet++ was necessary to become the values comparable, since omnet++ returns the generic pathloss and the MATLAB returns received power at receiver, which was standardized as standard comparison unit, in dB. Furthermore, these comparisons were done only in the obtained values referring to large-scale signal, once the small-scale signal values varying according to a normal distribution. The validation of the small-scale signal will be dealt later in this same section.

The common simulation parameters for all test scenario is depicted in Table 3.1.

Table 3.1: Simulation parameters.

| | |
|----------------------|-------------|
| Operating Frequency | 5.89 GHz |
| Transmit Power | 23.0103 dBm |
| Antenna Gain | 0 dBi |
| Antenna Polarization | Vertical |

3.2.1 LOS Link Type

Scenario 1

The first test scenario for LOS channel (Figure 3.3) simulates two vehicles leaving from same point with six seconds delay each other and moving in same way at almost constant speed. Despite of the fact that the acceleration had set to zero, there was a small speed variation throughout the path. The antenna position of both cars is placed in the middle of the car and there is no static object and any other car on this scenario, featuring a LOS channel. Other specifications are found in Table 3.2.

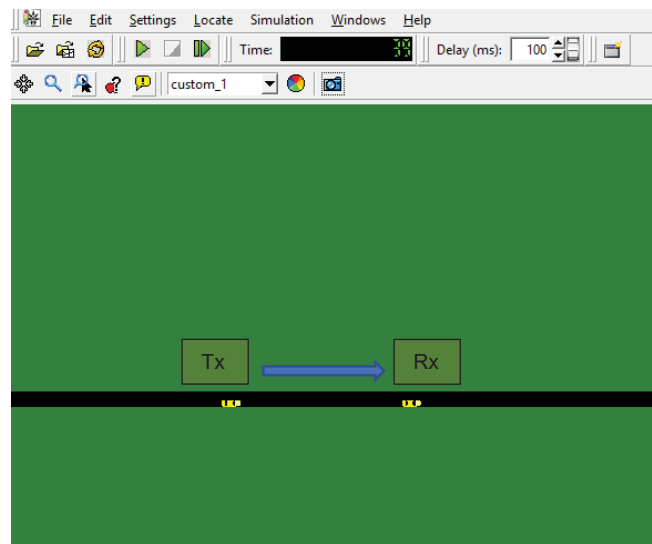


Figure 3.3: First test-scenario setup for the LOS channel on SUMO.

Table 3.2: Specifications for the first LOS test-scenario.

| Specification | Value (I.S.) |
|--------------------------------|--------------|
| Number of vehicles | 2 |
| Vehicle's way | Same |
| Width | 2 |
| Length | 4 |
| Total height (vehicle+antenna) | 1.5 |
| Antenna position | Middle |

| | |
|---------------|----|
| Acceleration | ~0 |
| Depart speed | 10 |
| Lanes per way | 1 |

The goal is to maintain a constant scenario without external interference, where results almost constant are expected. The “almost constant” refers to the speed variation (positive and negative) that was not possible to keep it constant on Sumo. In Figure 3.4 is shown the speed (m/s²) in relation to the timestep (s) over the transmitter (orange line) and receiver (blue one). For both vehicles has obtained a mean speed value at 10,35 m/s² with a variation of +/- 0,6 m/s².

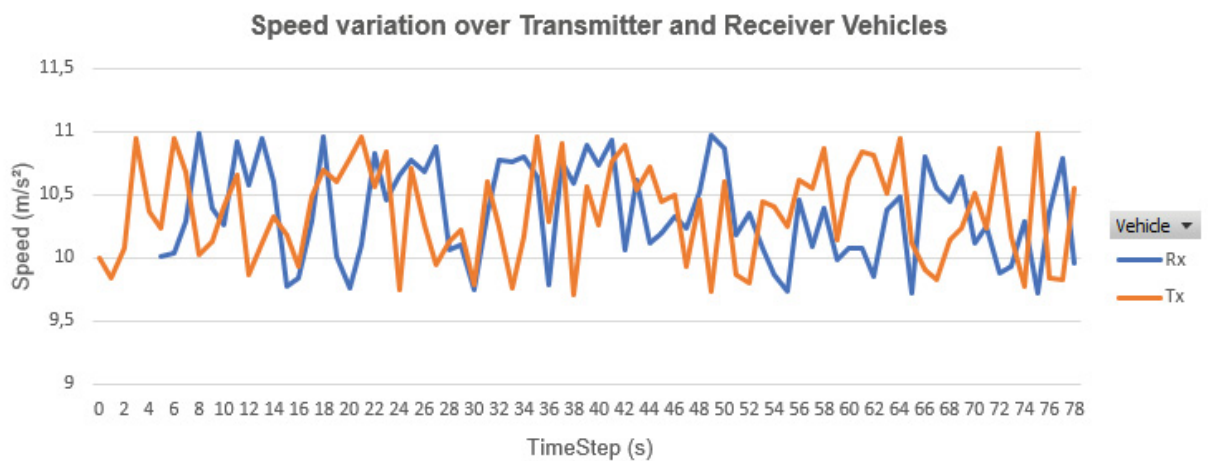


Figure 3.4: Speed variation.

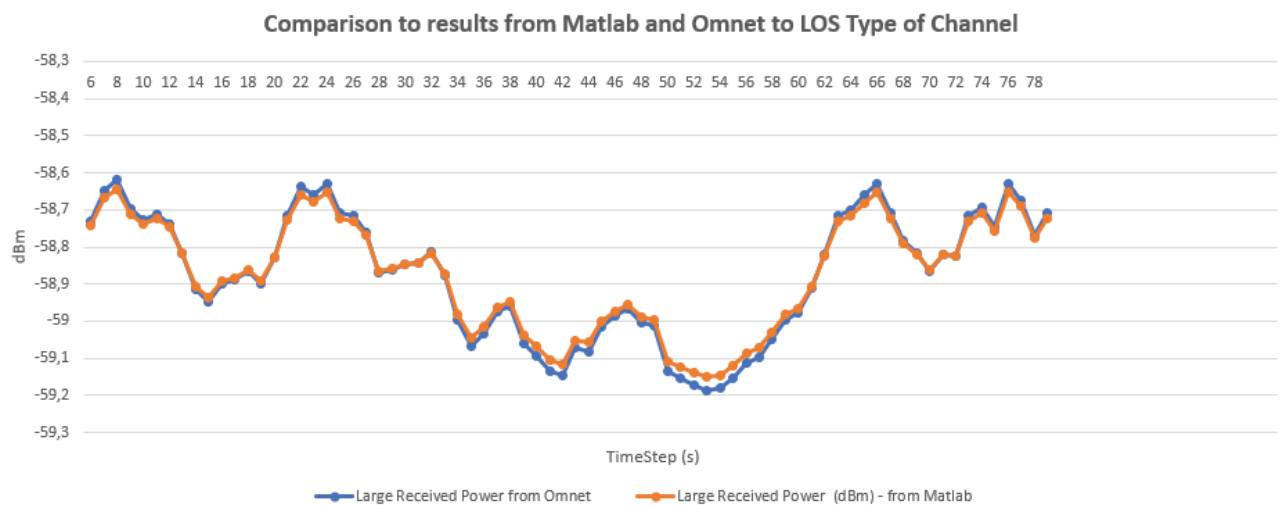


Figure 3.5: Received power measurement for the first LOS test-scenario.

The Figure 3.5 shows the received power over the timestep in seconds. It was obtained a mean value at -58.9 dBm with a variation of roughly $\pm 0,3$ dB that comes from small acceleration variation. In addition, it is observed a good match between data from MATLAB and omnet++ using GEMV² model, thereby validating the model over this first scenario.

Scenario 2

The second test scenario for LOS channel differs from the first one in the following items: the vehicles are moving in opposite direction (Figure 3.6) with an initial distance of 1000 meters each other; They have a positive acceleration of an initial speed at 1m/s. Moreover, it was varied the size of antenna. The entire scenario specification is found in Table 3.3.

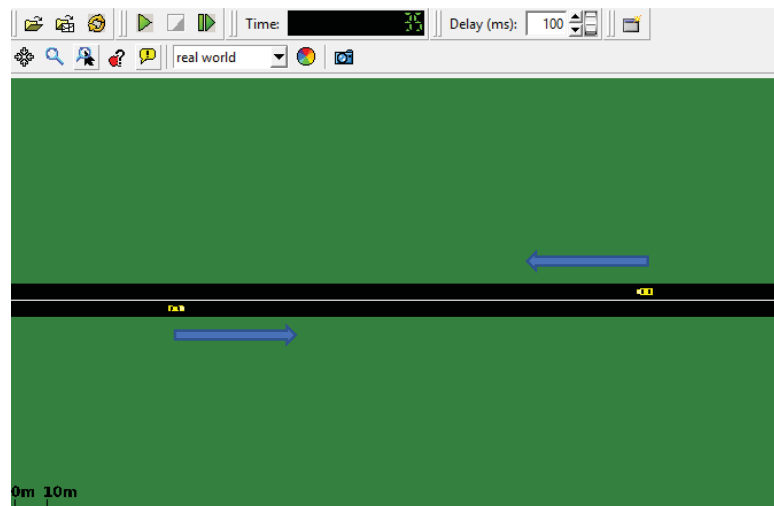


Figure 3.6: Second test-scenario setup for the LOS channel on SUMO.

Table 3.3: Specifications for the second LOS test-scenario.

| Specification | Value (I.S.) | | |
|--------------------------------|-------------------|------------|------------|
| | Scenario 1 | Scenario 2 | Scenario 3 |
| Number of vehicles | 2 | | |
| Vehicle's way | Opposite | | |
| Width | 2 | | |
| Length | 4 | | |
| Total height (vehicle+antenna) | 1,5 | 4 | 1 |
| Antenna position | Middle of vehicle | | |
| Acceleration | 2,6 | | |
| Depart speed | 1 | | |
| Lanes per way | 1 | | |

These changes aim to change the main two variables of the Two Ray Ground Model – distance between antennas and set size composed by antenna and vehicle height.

In Figure 3.7 is demonstrated the variation of received power in relation to the timestep in each setup created, where the orange line represents the vehicle and antenna height based setup with 1,5 meters, the grey one with 1,0 meter and the blue one with 4,0 meters. Correctly, when the cars get closer each other, the received power increases proportionally and as the cars move away from each other, the received power returns back to lower levels with the same proportionally. Another interesting point is in relation to the system's performance to each setup. The setup with antenna and vehicle's height equal 1,5 meters had the best performance than other ones. At timestep 41, the cars are nearest each other, the difference is about -20 dB to the third setup.

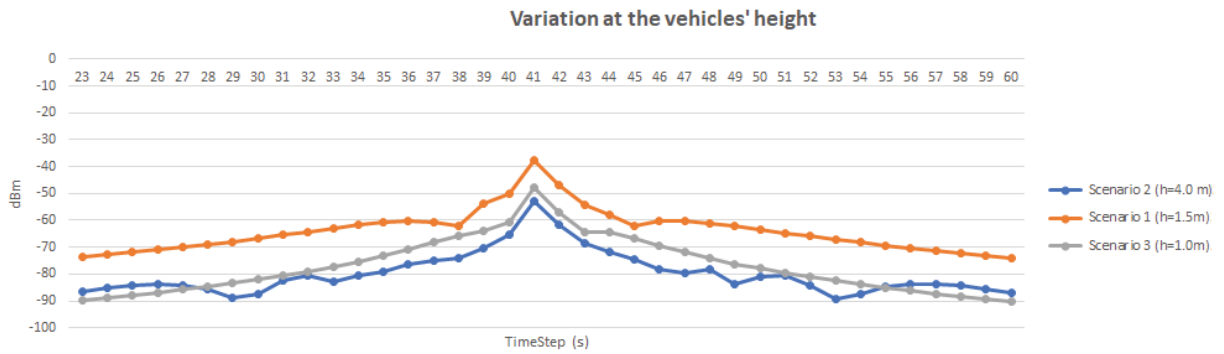


Figure 3.7: Received power measurement for the second LOS test-scenario.

The match of data from Omnet++ and MATLAB were fulfilled for this scenario too, as it can be seen in Figure 3.8, which represents the percentage value of difference between the Omnet++ and MATLAB's data in relation to the timestep over the 03 setups. At timestep 41s had the largest difference to both setups, however, it is extremely derisory and might be linked a small position variation.

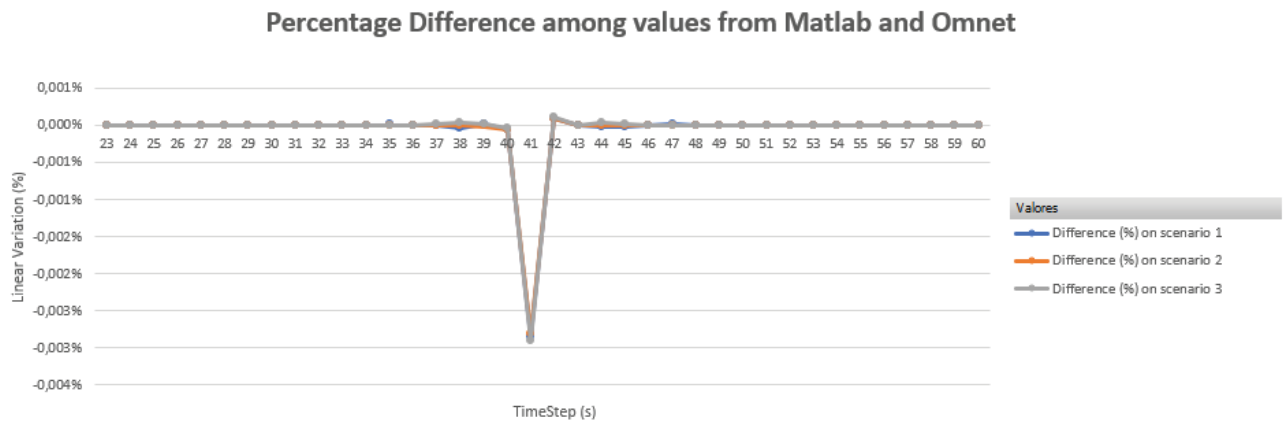


Figure 3.7: Divergences on the received power measurements for the second LOS test-scenario.

Scenario 3

The third scenario keeps the same configuration of the second scenario, except for the fact that the antenna and vehicle's height were fixed at 1,5 meters. The idea behind this scenario is to change the antenna position over the car in order to check the impact

thereof. It was possible, because was created an external module on omnet++ to reallocate the antenna position over the vehicle which prior was at front of the car (come from SUMO's setting).

On MATLAB's setting the antenna position has been placed at middle of the car and would demand too much effort to change it all. Because of that, it was not possible to compare the results of both implementations for this scenario. The entire scenario specification is found in Table 3.4.

Table 3.4: Specifications for the third LOS test-scenario.

| Specification | Value (I.S.) | | |
|--------------------------------|--------------|------------|------------|
| | Scenario 1 | Scenario 2 | Scenario 3 |
| Number of vehicles | 2 | | |
| Vehicle's way | opposite | | |
| Width | 2 | | |
| Length | 4 | | |
| Total height (vehicle+antenna) | 1,5 | | |
| Antenna position | Rear | Middle | Front |
| Acceleration | 2.6 | | |
| Depart speed | 1 | | |
| Lanes per way | 1 | | |

In Figure 3.9 is represented the received power values according to each configuration of the antenna position. The blue, orange and grey lines represents the antenna position at middle, rear and front on the vehicle respectively. According to the measurements shown in Figure 3.9, there is no expressive variation regarding the antenna position over the car.

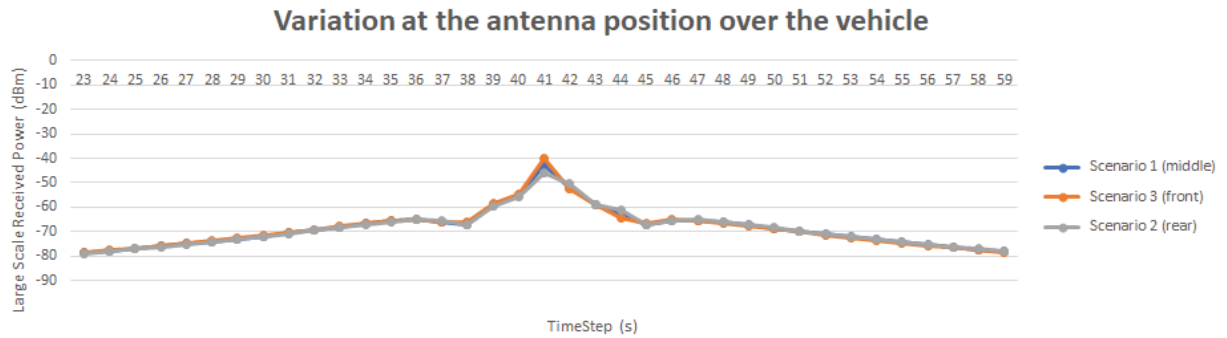


Figure 3.9: Received power measurement for the third LOS test-scenario.

3.2.2 NLOSv Link Type

Scenario 1

The first test scenario for NLOSv channel considers the same aspect of first LOS test scenario, with one more vehicle though (Figure 3.10). The third car is added in order to obtain a car for intercepting the communicating pair, featuring a NLOSv channel. The antenna position of both cars is located in the middle of the car and there is no static object. The full scenario specification is found in Table 3.5.

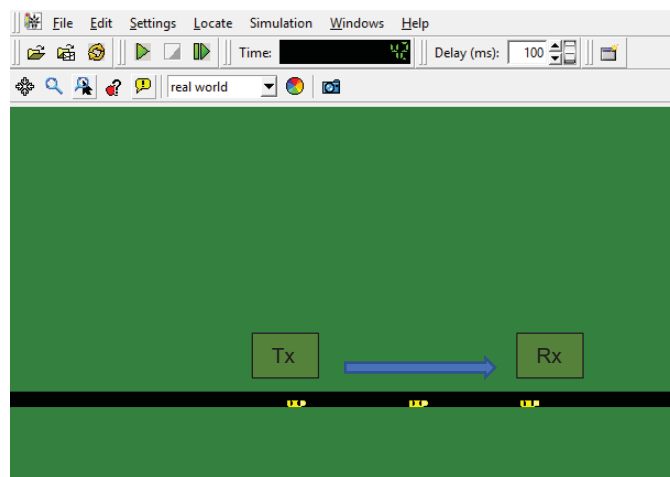


Figure 3.10: First test-scenario for the NLOSv channel on SUMO.

Table 3.5: Specifications for the first NLOSv test-scenario.

| Specification | Value (I.S.) |
|--------------------------------|--------------|
| Number of vehicles | 3 |
| Vehicle's way | Same |
| Width | 2 |
| Length | 4 |
| Total height (vehicle+antenna) | 1.5 |
| Antenna position | Middle |
| Acceleration | ~0 |
| Depart speed | 10 |
| Lanes per way | 1 |

The received power measurements in relation to the timestep and Tx and Rx's indexes for this scenario are presented in Figure 3.11. It was obtained a mean value at -60,81 dBm with a variation about +/- 0,4 dB that comes from acceleration small variation (same from Figure 3.4). Moreover, it also observes a good match between data from MATLAB and omnet++, thereby validating the model over this first scenario.

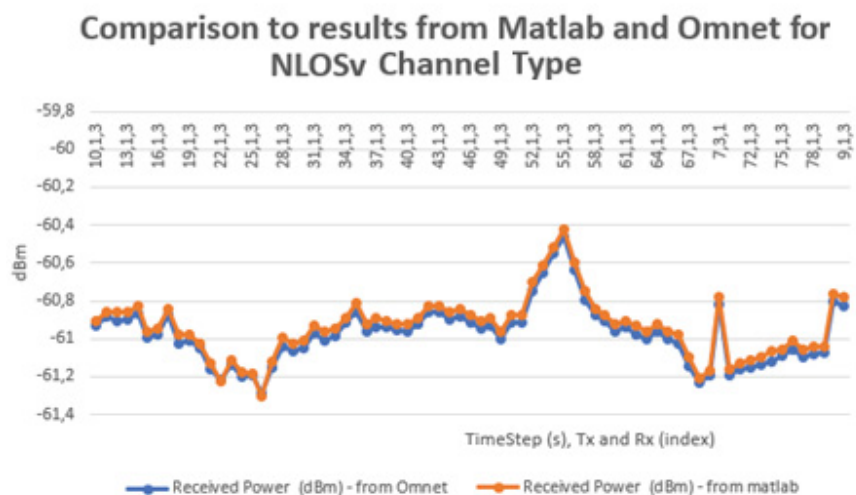


Figure 3.11: Received power measurement for the first NLOSv test-scenario.

Scenario 2

In order to configure a more realist scenario and consider other important variables for the knife-edge obstacle model like the number of vehicles that obstructs the line of sight and hurdle's penetration rate (obstructing vehicle's height and width), it has been taken the first NLOSv test-scenario and added more vehicles in both ways. Besides that, the impact of the vehicles' height variation was evaluated by varying only the height of the communicating vehicles (Tx and Rx). The entire scenario specification is found in Table 3.6.

Table 3.6: Specifications for the second NLOSv test-scenario.

| Specification | Value (I.S.) | | |
|--------------------------------|--------------|------------|------------|
| | Scenario 1 | Scenario 2 | Scenario 3 |
| Number of vehicles | 8 | | |
| Vehicle's way | both | | |
| Width | 2 | | |
| Length | 4 | | |
| Total height (vehicle+antenna) | 1,5 | 4 | 1 |
| Antenna position | Middle | | |
| Acceleration | 2.6 | | |
| Depart speed | 1 | | |
| Lanes per way | 2 | | |

The receiver power measurements according to the height variation are shown in Figure 3.12. At higher level, the dark blue and green lines represent values referring to vehicles with height at 1,5 and 4,0 meters respectively from Omnet. Similarly for the yellow and green ones respectively, although the values are from MATLAB. At lower level, the orange and light blue ones represent the setting with height at 1.0 meter from Omnet and MATLAB respectively. It is noticed from those results a good match between data from MATLAB and Omnet and also observed a worst performance when the height is set at

1,0m of about -5 dB. It might have happened by the fact that taller vehicles are more likely to block reflection coming from building walls or other vehicles.

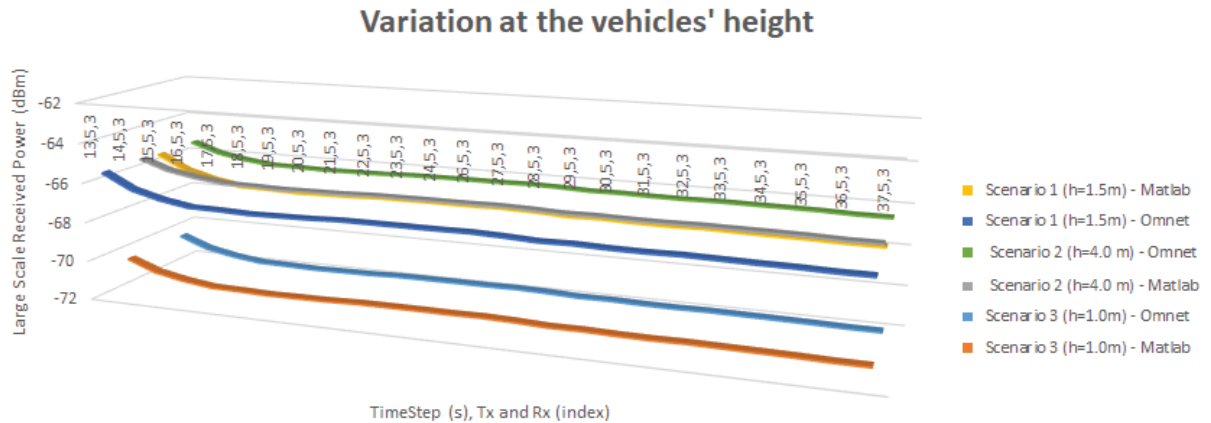


Figure 3.12: Received power measurements for the second NLOSv test-scenario.

Scenario 3

The third test-scenario for the NLOSv channel differs from the second one by changing vehicles' width instead of changing their height – another variable of the penetration rate of the knife-edge model as mentioned above. The entire scenario specification is found in Table 3.7.

Table 3.7: Specifications for the third NLOSv test-scenario.

| Specification | Value (I.S.) | | |
|--------------------------------|--------------|------------|------------|
| | Scenario 1 | Scenario 2 | Scenario 3 |
| Number of vehicles | 8 | | |
| Vehicle's way | both | | |
| Width | 2 | 3 | 4 |
| Length | 4 | | |
| Total height (vehicle+antenna) | 1,5 | | |
| Antenna position | Middle | | |
| Acceleration | 2.6 | | |

| | |
|---------------|---|
| Depart speed | 1 |
| Lanes per way | 2 |

Despite of these changes, in Figure 3.13 observes that did not occur any variation at the received power by varying the cars' width. Both scenarios have the same received power and therefore, the GEMV² model is little influenced by the variation of the vehicle width.

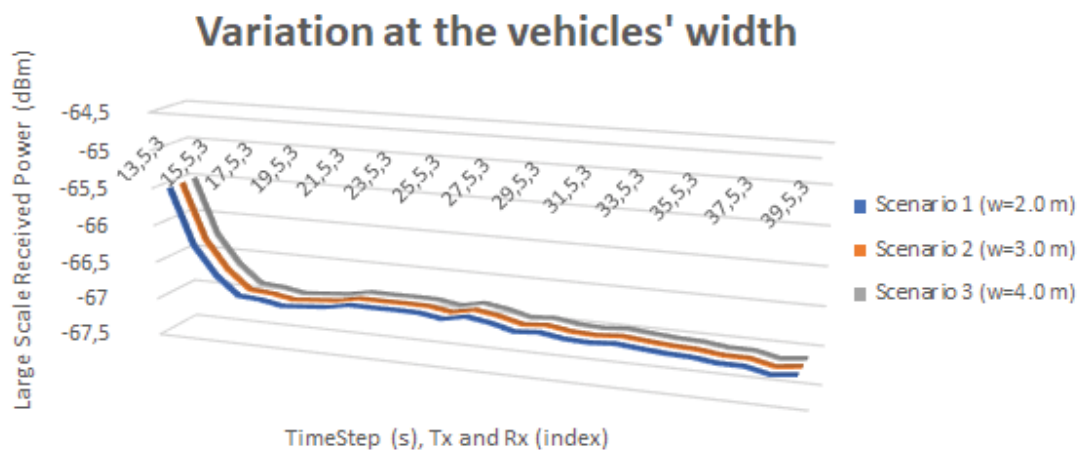


Figure 3.13: Received power measurements for the third NLOSv test-scenario on Omnet.

3.2.3 NLOSb Link Type

Scenario 1

A scenario with an crossing was created on SUMO in order to feature a test scenario for NLOSb channel. On that scenario was inserted two vehicles moving into this crossing and then moving out from it but keeping straight. In addition, four types of outlines were added as the static objects in attempt of creating different diffraction and reflection points as shown in Figure 3.14. These different geometries interfere in reflection and diffraction model's parameters. The length of the roadways are 300 meters, so that the vehicles can communicate themselves since their departures. The entire scenario specification is found in Table 3.8.

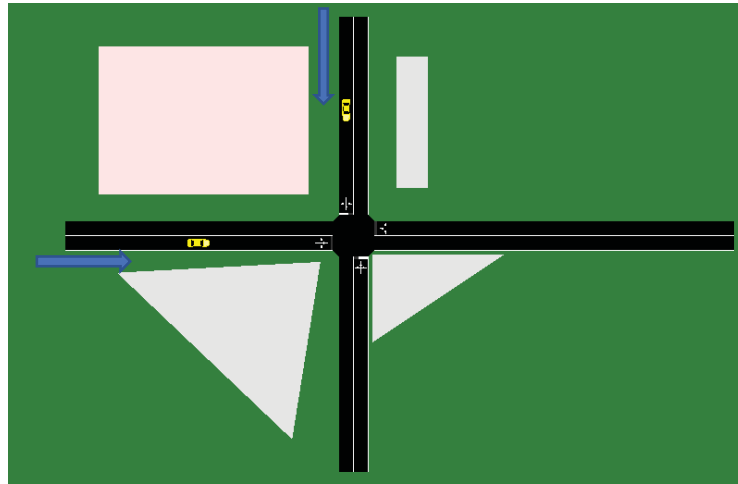


Figure 3.14: First test-scenario for the NLOSb channel on SUMO.

Table 3.8: Specifications for the first NLOSb test-scenario.

| Specification | Value (I.S.) |
|--------------------------------|-------------------|
| Number of vehicles | 2 |
| Vehicle's way | Mix |
| Width | 2 |
| Length | 4 |
| Total height (vehicle+antenna) | 1.5 |
| Antenna position | Middle of vehicle |
| Acceleration | 2,6 |
| Depart speed | 1 |
| Lanes per way | 1 |
| Length of roadways | 300 |

This scenario operates under two models: log-distance and reflection-and-diffraction (geometric) models. The receiver power measurements obtained from these models are shown in Figure 3.15. The blue and grey lines represent the log-distance and geometric models respectively on MATLAB. The blue one is not visible on graph because is completely under of the yellow one. On the other hand, the yellow and orange ones are

respectively on Omnet. There is noticeable a good fit between the data from MATLAB and Omnet when operated over the log-distance model. However, the measurements regarding the reflection and diffraction model came out with a constant offset roughly -30 dB between MATLAB and Omnet over whole path. These variations might have occurred due to the different simplifications referring to the static objects' outlines.

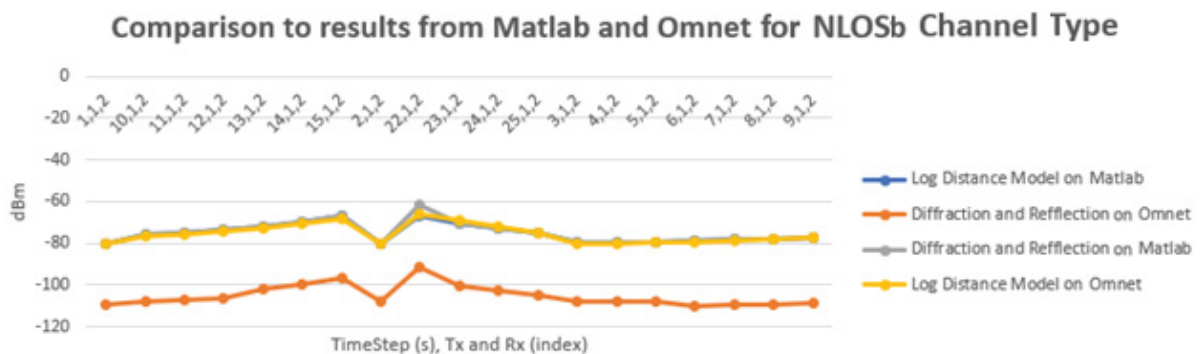


Figure 3.15: Received power measurements for the first NLOSb test-scenario.

Scenario 2

The second test scenario for NLOSb channel is also a crossing, however, the static-objects and roadway's outlines were modified if compared to the first scenario, so that the scenario become more realist and explore different conditions through different geometries, especially for reflection and diffraction model. In addition, three more cars were added which depart according to blue arrows in Figure 3.16. The full scenario specification is found in Table 3.9.

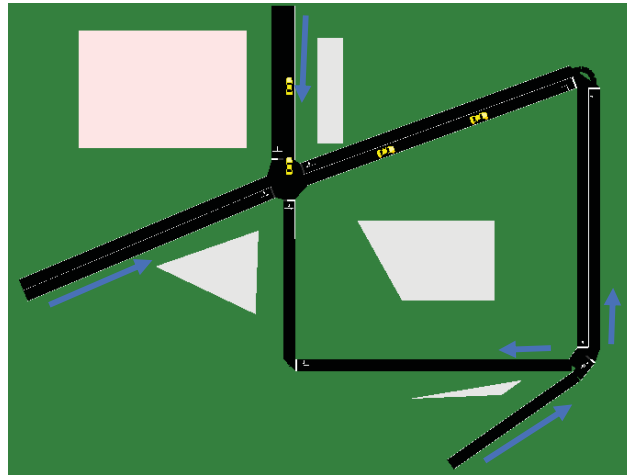


Figure 3.16: Second test scenario for the NLOSb channel on SUMO.

Table 3.9: Specifications for the second NLOSb test-scenario.

| Specification | Value (I.S.) |
|--------------------------------|-------------------|
| Number of vehicles | 4 |
| Vehicle's way | mix |
| Width | 2 |
| Length | 4 |
| Total height (vehicle+antenna) | 1.5 |
| Antenna position | Middle of vehicle |
| Acceleration | 2,6 |
| Depart speed | 1 |
| Lanes per way | 1 |

In Figure 3.17 is detailed the received power values according to the correspondent timestep and communication pair's indexes. The blue and yellow lines represent the log-distance and geometric models respectively on MATLAB. The blue one is not visible on graph because is completely under of the grey one. On the other hand, the grey and orange ones are respectively on Omnet.

Likewise that the first scenario, there were a good match between the data between MATLAB and Omnet when used the log-distance model and, an offset roughly -30 dB arose over whole path when used the geometric model.

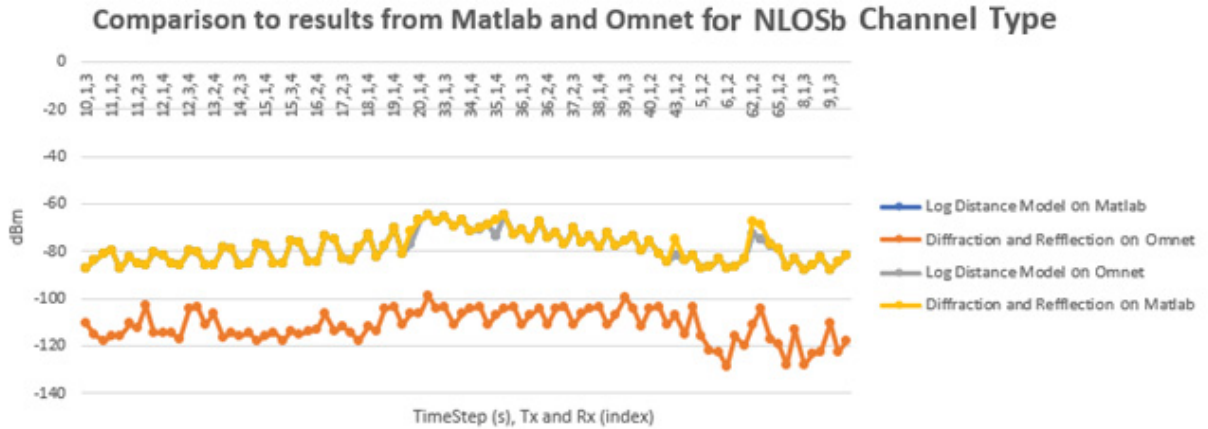


Figure 3.17: Received power measurements for the second NLOSb test-scenario.

3.3.4 Validation of small-scale signal variation

The small-scale signal was obtained through a normal distribution with mean value 0 and standard deviation σ (BOBAN, 2014). So, basically, if it ensures that the standard deviation is equal for both MATLAB and Omnet++ on scenarios tested above, ensures the validation of small-scale signal. In order to simulate the small-scale signal for all scenarios above was used 10 as standard value for both NV_{max} and AS_{max} .

The standard deviations obtained in each scenario from both MATLAB and Omnet are shown in Table 3.10. All LOS scenarios had the same standard deviation, since both has the same number of vehicles and the same area of static objects (LOS scenarios do not have any static object over test scenarios) inside the communication ellipse. Likewise that the scenarios 1 and 2 of the NLOSv channel.

Table 3.10: Standard deviation of the test-scenarios

| Scenarios | Standard Deviation on Omnet++ | Standard Deviation on MATLAB | Difference |
|--------------------|-------------------------------|------------------------------|--------------|
| LOS – Scenario 1 | 3,300849706 | 3,29428006 | 0,006601699 |
| LOS – Scenario 2 | 3,300849706 | 3,29428006 | 0,006601699 |
| LOS – Scenario 3 | 3,300849706 | 3,29428006 | 0,006601699 |
| NLOSv – Scenario 1 | 3,80102698 | 3,808629034 | -0,007602054 |

| | | | |
|--------------------|-------------|-------------|--------------|
| NLOSv – Scenario 2 | 3,301300841 | 3,307903443 | -0,006602602 |
| NLOSv – Scenario 3 | 3,301300841 | 3,307903443 | -0,006602602 |
| NLOSb – Scenario 1 | 4,18016463 | 4,171804301 | 0,008360329 |
| NLOSb – Scenario 2 | 4,179426844 | 4,17106799 | 0,008358854 |

3.3.5 Final considerations

After performing all the test simulations mentioned above and obtaining from those coherent values, some aspects deserve to be highlighted:

- The most models have had a reasonable match between the values from MATLAB and Omnet, thereby ensuring a correct implementation.
- Despite of having an offset roughly -30 dB over geometric model, even changing some key parameters, the offset value has kept constant over the whole path and over scenarios with different features, thereby characterizing a reliable system. These variations might have occurred due to the different simplifications referring to the static objects' outlines.
- The small-scale signal has shown a negligible small variation.

4 IMPACTS OF GEMV² MODEL INTO ARTERY

After ensuring that the GEMV² model has been implemented into the Artery simulation framework correctly, the real impact of the model was demonstrated through a comparison between values came from the traditional radio propagation models used by Artery till then and the GEMV² model implemented. Furthermore, in order to obtain a more robust and realistic comparison, the simulation was carried out over a map and traffic model well known in the literature – so-called Luxembourg SUMO Traffic (LuST) Scenario (Figure 4.1), which is composed by more than 4k cars, 14.174 polygons and 155.95 km² of area (CODECA et. al., 2017). However, due to the large simulation time that would take to simulate the whole scenario, the comparison was carried out at a specific time interval (t=30'' till t=5'14), which demonstrated a steady and common daily traffic scenario.



Figure 4.1: LuST Scenario Topology (CODECA et. al., 2017).

According to Rappaport (2000), in order to model the small-scale signal over LOS and NLOS environments is recommended using the Rice or Nakagami Distribution and the Rayleigh Distribution respectively. The two-ray model was picked for large scale instead of the free-space model, once it is more realistic and because there were only the two in the framework. In addition, the simulation parameters were used the same as those used in the previous section.

The received power measurements during the specific time interval for the LuST scenario are presented in Figure 4.2. More than 4.000 points were simulated, which the grey ones are referring to the GEMV² model and the yellow ones are referring to the traditional models. The light-brown line indicates the threshold power at receiver (-85 dBm).

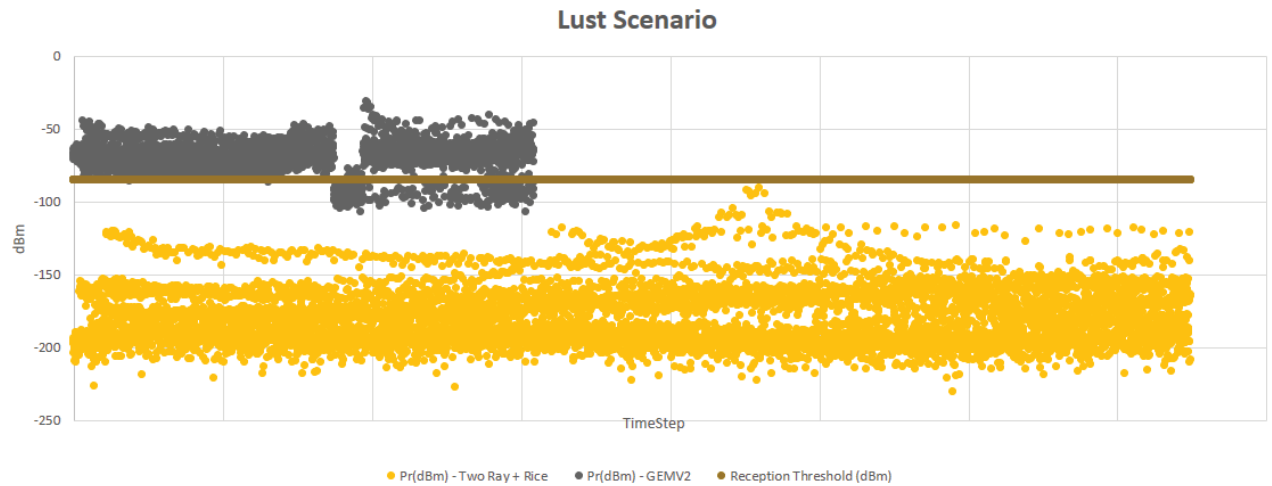


Figure 4.2: Received power measurements over LuST scenario. Number of data points: 4129.

The GEMV² model has a better estimation for vehicular environments regarding the received power, in such a way that the receiver change from “not decodable” to “decodable”, once the reception threshold is set at -85 dBm at Artery. Furthermore, it is observed so many point from timestep=106,5s that not even appear over GEMV² model. It happens because of the Artery’s previous condition that had a communication range of 1.000 meters for all link types while GEMV² model limits the communication range to 500, 400 and 300 meters for the LOS, NLOSv and NLOSb link types respectively, and on the LuST scenario, from timestep=70s, the vehicles reach a distance larger than 500 meters each other.

A second comparison was made based on an UFPR’s campus customized map and traffic model. Once this new scenario is predominately filled by buildings and has a length much smaller if compared to the LuST scenario, added the heavy traffic, this scenario is featured as NLOS environment mostly. Therefore, the Rayleigh distribution was used for small scale instead of Rice distribution.

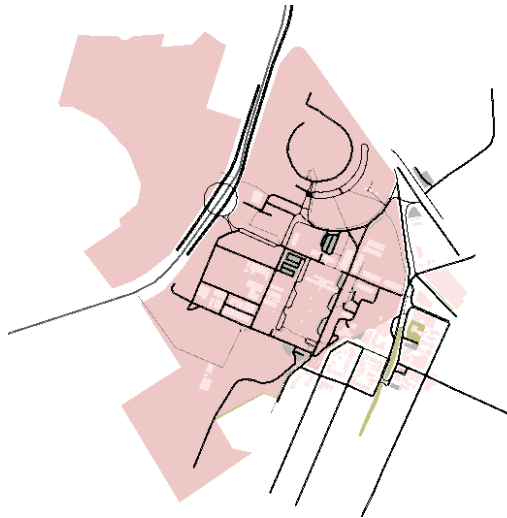


Figure 4.3: UFPR Scenario Topology.

A condition very similar also happened with the second scenario. In Figure 4.4 the yellow measurements referring to the GEMV² model and the orange ones referring to the Rayleigh and two-ray models. The simulation time reached almost 5,5 minutes.

Likewise that the first scenario, a received signal's optimization about 82,30 dB emerged when applied the GEMV² model and at end of simulation, when the vehicles are leaving the map and/or the distance between them are getting larger, the received signal disappears.

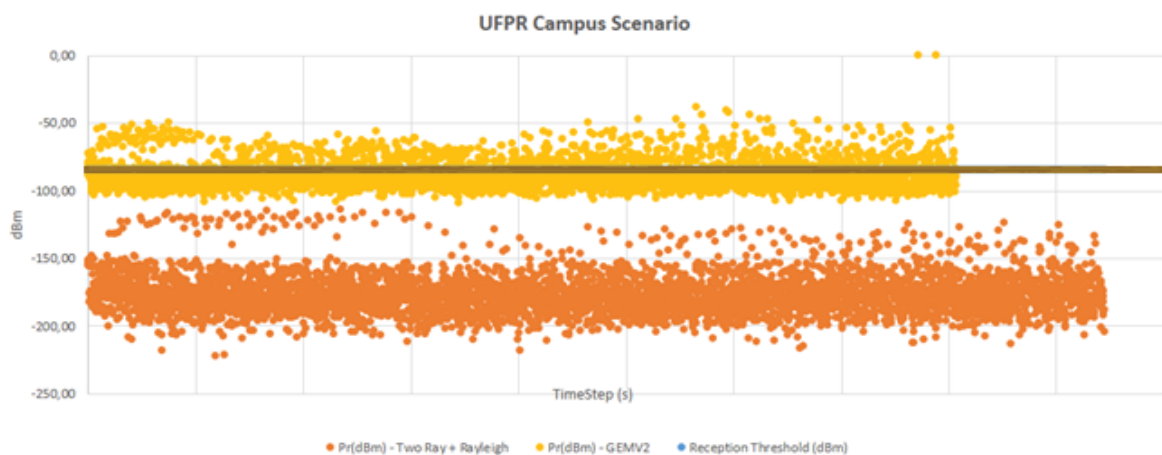


Figure 4.4: Received power measurements over UFPR scenario. Number of data points: 5.221.

The optimization upon both comparisons might have relation to the GEMV² model's geometric considerations (reflections and diffraction methods), that increment the large-scale received power and the fact of normal distribution be much less severe than Rice and Rayleigh models for small-scale signal.

5 CONCLUSION AND FURTHER WORK

The main target of this dissertation was to implement the GEMV² model, which considers the impact of the vehicles over the communication channel and is an efficient model for realist large-scale simulation with thousands of communicating vehicles in various vehicular environments, into the Artery simulation framework for VANET applications. The GEMV² model classifies the vehicular environment in three types: Line of sight (LOS), non-line of sight due to vehicle (NLOSv) and non-line of sight due to buildings and foliages (NLOSb). That said, in the chapter 2 was done a bibliographic research involving the corresponding topics like simulator frameworks and radio propagations models in order to gather a knowledge base for building a methodology for implementation, in turn, was presented in chapter 3. One first achievement was an optimization on the source code of more than 50 functions on MATLAB to only 8 classes on omnet++. Part of it, it is related to the use of object oriented programming c++ itself and also the use of some boost libraries.

In order to validate the methodology of implementation, chapter 4, several test scenarios were created based on the main parameters of each model. The results had a good match between the values from MATLAB and Omnet in most models. Despite of having an offset roughly -30 dB over reflection and diffraction model (applied in NLOSb channel) between both implementations, the implementation showed itself reliable since the offset value has kept constant over the whole path and over scenarios with different features. These variations might have occurred due to the different implementation referring to the static objects' outlines, that are important, once they might change the diffraction and reflection points.

The GEMV² model presented itself highly sensitive to positioning variation (antenna position over the car, vehicle itself on the lane). Through antenna position adjustment setting created on Omnet, noticed that the setting with height set at 1,5 meters and on middle of the vehicle, whose was tested on LOS and NLOSv channel, demonstrated best performance in relation to the other. It might have happened by the fact that taller vehicles are more likely to block reflection coming from building walls or other vehicles.

Last but not least, the Artery simulation framework operating with the GEMV² model proved to become the simulation more realistic and with a good accuracy/scalability tradeoff through comparisons between the traditional radio propagation models used by Artery till then and the GEMV² over large scenarios. The received power measurements have been optimized about 82,3 dB. Similar gains were also obtained in (VIRIYASITAVAT et. al., 2015).

As a suggestion for further works, it would be interesting to redesign the INET framework in order to insert more performance parameters referring to the physical layer that are well known and used in the research environment, however it is missing out on Omnet. The current simulation framework uses only noise and received power as performance indicative.

REFERENCES

802.11 Part 11: Wireless LAN Medium Access Control (MAC) and Physical Layer (PHY) Specifications; **Institute of Electrical and Electronics Engineers**, Mar. 2012.

ALVES, R. S. et al.; “Redes veiculares: Princípios, aplicações e desafios”. In: **SBRC. 27 Simpósio Brasileiro de Redes de Computadores e Sistemas Distribuídos - SBRC.2009**.

BOBAN, M.; BARROS, J.; TONGUZ, O. K.; “Geometry-Based Vehicle-to-Vehicle Channel Modeling for Large-Scale Simulation”. **IEEE Transaction on vehicular technology**, vol. 63, nº. 9, Nov. 2014.

BOBAN, M.; VINHOZA, T. T. V.; FERREIRA, M.; BARROS, J.; TONGUZ, O. K.; “Impact of Vehicles as Obstacles in Vehicular Ad Hoc Networks”. **IEEE Journal on selected areas in communications**, vol. 29, nº. 1, Jan. 2011.

CAMPOLO, C.; MOLINARO, A.; Multichannel communications in vehicular ad hoc networks: a survey. **IEEE Commun. Mag.**, 51 (5) (2013), pp. 158–169, 10.1109/MCOM.2013.6515061 CrossRefView Record in Scopus.

CHENG, L.; HENTY, B. E.; STANCIL, D. D.; BAI, F.; MUDALIGE, P.; “Mobile vehicle-to-vehicle narrow-band channel measurement and characterization of the 5.9 GHz dedicated short range communication (DSRC) frequency band” **IEEE J. Sel. Areas Commun.**, vol. 25, no. 8, pp. 1501–1516, Oct. 2007.

CHOFFNES, D. R. et al.; An integrated mobility and traffic model for vehicular wireless networks. In: **ACM International Workshop on Vehicular Ad Hoc Networks**. 2005.

CODECA, L.; FRANK, R.; FAYE, S.; ENGEL, T.; “Luxembourg SUMO Traffic (LuST) Scenario: Traffic Demand Evaluation” in **IEEE Intelligent Transportation Systems Magazine**, vol. 9, no. 2, pp. 52-63, Summer 2017.

CORMEN, T. H.; LEISERSON, C.; RIVEST, R. L.; STEIN, C.; “Algorithmen – Eine Einführung” in **2. ed. München: Oldenbourg Wissenschaftsverlag**. pp. 585–586. 2007.

ETSI, EN 302 665 - Intelligent Transport Systems (ITS); Communications Architecture, V1.1.1, **European Telecommunications Standards Institute**, Sep. 2010.

ETSI, Final draft ETSI ES 202 663 V1.1.0 (2009–11), **ETSI standard**, intelligent transport systems (ITS); European profile standard for the physical and medium access control layer of intelligent transport systems operating in the 5 GHz frequency band, November 2011.

GRINSTEAD, C. M.; SNELL, J. L.; Introduction to Probability. **American Mathematical Society**. 2nd edition, 1998.

IEEE Guide for Wireless Access in Vehicular Environments (WAVE) - Architecture. IEEE Std1609.0-2013, p. 1–78, March 2014.

Intelligent Transport Systems (ITS); Users and applications requirements; Part1: Facility layer structure, functional requirements and specifications, **European Telecommunications Standards Institute**, Aug. 2013.

Intelligent Transport Systems (ITS); Vehicular Communications; Basic Set of Applications; Part 2: Specification of Cooperative Awareness Basic Service, ETSI EM 302 637-2, **European Telecommunications Standards Institute**, Nov. 2014.

Intelligent Transport Systems (ITS); Vehicular Communications; GeoNetworking; Part 4: Geographical addressing and forwarding for point-to-point and point-to-multipoint communications; Sub-part 1: Media-Independent Functionality, ETSI EN 302 636-4-1, **European Telecommunications Standards Institute**, Jul. 2014.

Intelligent Transport Systems (ITS); Vehicular Communications; GeoNetworking; Part 5: Transport Protocols; Sub-part 1: Basic Transport Protocol, **European Telecommunications Standards Institute**, Aug. 2014.

ITU-R, “Propagation by diffraction,” **International Telecommunication Union Radio-communication Sector**, Geneva, Recommendation P.526, Feb. 2007.

KAKKASAGERI, M. et al. Information management in vehicular ad hoc networks: A review. **Journal of Network and Computer Applications**, v. 39, n. 0, p. 334 – 350, 2014. ISSN 1084-8045.

KOLLER, M.; ELSTER, A.; REHBORN, H.; KERNER, B. S.; “A system for vehicle data processing to detect spatiotemporal congested patterns: The SIMTD-approach” 19th **ITS World Congress**, Vienna, Austria, 22/26 Oct. 2012.

MANGEL, T.; MICHL, M.; KLEMP, O.; HARTENSTEIN, H.; “Real-world measurements of non-line-of-sight reception quality for 5.9 GHz IEEE802.11p at intersections,” in **Proc. 3rd Int. Conf. Commun. Technol. Vehicles**, ser. Nets4Cars/Nets4Trains, Berlin, Germany, 2011, pp. 189–202, Springer-Verlag.

MAURER, J.; FUGEN, T.; SCHAFER, T.; WIESBECK, W.; “A new inter-vehicle communications (ivc) channel model,” in Proc. **IEEE 60th Vehicular Technology Conference (VTC 2004-Fall)**, vol. 1, Sept. 2004, pp. 9–13.

NAGEL, K. et al.; A cellular automaton model for freeway traffic. **Journal de Physique**, v.2, n. 12, December 1992.

- OBERMAIER, C.; "Real-Time Testing of Car2X Hardware with OMNeT++", **Report of Master Degree. Technische Hochschule Ingolstadt**. Computer Science Faculty. 2017.
- PEREIRA, M. A.; "Análise de modelos de propagação na área urbana da região de Curitiba/PR na faixa de frequência de 1800 MHz", **Dissertation of Master Degree. Federal University of Parana**. DELT. 2007.
- RAPPAPORT, T. S.; **Wireless Communications: Principles and Practice**. Englewood Cliffs, NJ, USA: Prentice-Hall, 1996.
- RAPPAPORT, T. S.; **Wireless Communications: Principles and Practice**. Prentice-Hall PTR. 2000.
- RIEBL, R.; OBERMAIER, C.; FACCHI, C.; NEUMEIER, S.; "Vanetza: Boosting Research on Inter-Vehicle Communication". [Online]. Available: <https://github.com/riehl/vanetza>.
- RIEBL, R.; GUNTHER, H. J.; FACCHI, C.; WOLF, L.; "Artery: Extending Veins for VANET applications", in **Models and Technologies for Intelligent Transportation Systems (MT-ITS)**, 2015 International Conference on, Jun. 2015, pp. 450–456. [Online]. Available on: <https://github.com/riehl/artery>.
- SILVA, R.; "Características da Propagação ponto-área na faixa de 2 a 15 GHz com aplicações em Comunicações Móveis". **Dissertation of Master Degree. Military Institute of Engineering**. Rio de Janeiro, 2004.
- SIZENANDO, F.; "Avaliação dos Modelos de Predição de Propagação para Telefonia Móvel Celular na Cidade de Natal". **Dissertation of Master Degree. Federal University of Rio Grande do Norte**. Natal, 2006.
- SOMMER, C.; **Veins Documentation**. [Online]. Available on: <http://veins.car2x.org/documentation/>.
- SUMO. **Simulation of Urban Mobility**. December 2015. Road Traffic Simulator. Available on: <http://www.dlr.de/ts/en/desktopdefault.aspx/tabid-9883>.
- United States Department of transportation (USDOT)**. Planning Future Transportation: Connected Vehicles and ITS. 2016. Available on: http://www.its.dot.gov/factsheets/pdf/PlanningFutureTransportation_FactSheet.pdf
- VARGA, A. et al. **Omnet++ Simulation Framework**. Available on: <https://omnetpp.org/>.
- VIRIYASITAVAT, W.; BOBAN, M.; TSAI, H.; VASILAKOS, A. V.; "Survey and Challenges of Channel and Propagation Models". **IEEE vehicular technology magazine**. June, 2015.

XU, S.; SAADAWI, T.; “Does the IEEE 802.11 MAC Protocol Work Well in Multihop Wireless Ad Hoc Networks”, in **IEEE Communications Magazine, European Telecommunications Standards Institute**, jun. 2001, pp. 130–137.

WANG, C.-X.; CHENG, LAURENSEN, X. D. I.; “Vehicle-to-vehicle channel modeling and measurements: Recent advances and future challenges,” **IEEE Commun. Mag.**, vol. 47, no. 11, pp. 96–103, November 2009.