Performance Analysis of Routing Protocols on VANETs

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***Abstract*—This thesis proposal aims to create a test environment for several routing protocols in Ad Hoc vehicular networks where the type of communications is predominantly of V2X. In order to observe different performance indicators for analysis and comparison of various protocols, these will be tested over three topology-based routing protocols: AODV, OLSR, and DSDV in four different mobility environments including urban, highway, country and a realistic scenario of Lisbon. However, precedently, this thesis will focus on the theoretical concepts in an effort to gain context of the Ad Hoc vehicular networks that are going to be analyzed. Therefore, the concepts of how 5G will revolutionize the future of V2X communications and the current prism of Ad Hoc vehicular networks and its future will be addressed in this thesis. In addition, as this thesis aims to create a test environment for multiple protocols, all tools such as SUMO, NS3 and the created tool SUMO&NS3-Coupling will be subjects of a study so that this process can be carried out by someone in the academic world who desired to do a study in their own mobility scenarios.**

***Index Terms*—V2X; VANET; WAVE; 5G; AODV; OLSR; DSDV; VANET routing protocols.**

I. Introduction

OVER Over the past few decades, due to the rapid growth and evolution of our population in addition to needs that are constantly more demanding without any signs of deceleration, our society has been experiencing the benefits of new and more advanced mobile communications generations. Furthermore, this evolution of communications systems towards the current 5G telecommunication generation is expected to meet various communication requirements of future industrial or commercial fields. Currently, information and communication technology is not only the key driving factor for some of the most important innovations in the automotive industry, but also the future of Intelligent Transportation Systems (ITS). This is motivated by the consumer demand for a vast variety of ITS applications, for instance autonomous driving and, as a result, researchers are exploring new and more efficient network architectures, such as VANET (Vehicular Ad-hoc Network). VANETs have emerged as a fascinating research and application field. As an increasingly number of vehicles are being equipped with more and more technology such as sensors, processing and wireless capabilities are enabling a new paradigm of possibilities to revolutionise the ITS, more particularly in road safety, efficiency, and comfort. VANETs are a subclass of Mobile Ad-hoc NETwork (MANET) which belongs to a family of Wireless Ad-hoc NETwork (WANET). Regarding MANETs, they are fundamentally a self-organizing communication system that is not dependent on any infrastructure and is mostly used in military, however, nowadays it is gaining ground on civilian applications. Moreover, MANETs communications are equal to the basic communication methodology on Bluetooth ad hoc networks used for data sharing between mobile phones. At last, the basic principle of VANETs is the same as MANETs but, applied in vehicular scenarios where nodes are the cars with embedded sensors and communication systems or fixed infrastructure consisting of Road Side Units (RSU).

A. Goals and Contribution

The objective of this thesis is to create a simulation environment for various routing protocols in VANETs networks and in this way to take advantage of V2X communications. This environment has to be intuitive and easy to use, so that any student or researcher can use this environment to be able to make comparisons between the routing protocols. And for that, the SUMO&NS3-Coupling tool software was developed, this software will enable any student or researcher to seamlessly use the software to compare the routing protocols. Also, this thesis aims to provide a background on the theoretical concepts involved with VANET scenarios as well as the tools used.

B. Organization of the Document

This thesis is organized as follows:

- **II - Related Work:** This section is dedicated to all the surround work behind the goals of this thesis. Diving into the theoretical aspect of VANETs as well as overview of the most known routing protocols for vehicular networks. In addition, this section also gives a background of two key softwares to achieve the goals of this thesis, the NS-3 and SUMO.
- **III - SUMO&NS3-Coupling:** This section is strictly dedicated to the SUMO&NS3-Coupling program that I have developed to achieve the goal of this thesis. Starting with the architecture of the have a brief introduction to how the program work. Then, subsequently diving into each phase of the program, to full understand how it works. Starting with the creation of vehicular mobility scenarios until the end, then going through how SUMO&NS3-Coupling combines both SUMO and NS-3 until the last phase, with the analysis over the performance of each routing protocol.
- **IV - Conclusion & Future work:** The last section is dedicated to the conclusion thoughts and future work ideas.

II. Related Work

A. VANET

VANET or Vehicular Ad Hoc Networks are not the common type of network we are used to see in our daily basis where we have a fixed topology network where only the terminals are dynamically changing position, for instance the example of our phones. Therefore, in contrast, VANETs are a special case of a Mobile Ad Hoc Network (MANET) , highly dynamic and intermittent connected typologies networks due to the nature of constant and fast mobility of vehicles which bring new challenges to data communication and its QoS requirements [1]. VANETs will be essential to the new paradigm of autonomous driving and for intelligent transportation systems, and this new paradigm is not far away. Since, nowadays various automotive manufactures are already equipping their vehicles with onboard computing, sensors as well as wireless communications devices and navigation systems such as GPS in preparation to this new paradigm. However, this section will not only, but focus more on the technical aspect of the VANETs, diving into the routing protocols which is the main subject of this thesis.

1) Type of communication: Currently, the advances in mobile communications allow us different deployments of architectures for vehicular networks in urban areas, highways, and rural environments via ad hoc networks to support different applications and its QoS requirements. Therefore, a VANET regardless of the environment where it is operating, is going to utilize new types of communication between vehicles and fixed roadside equipment and infrastructure. These communications are grouped in what is called Vehicle-to-Everything (V2X), this group can be divided into the following communications: [2], [3]:

- **Vehicle-to-Vehicle (V2V):** Direct based communication that allows direct communication between vehicles without relying on the road side or fixed infrastructure.
- **Vehicle-to-Infrastructure (V2I):** Network based communication that allows communication between the vehicles to the infrastructure.
- **Vehicle-to-Pedestrians (V2P):** Direct based communication that allows direct communication between vehicle and pedestrians.
- **Vehicle-to-Network (V2N):** Network based communication that allows communication between the vehicles to the network.

Also, when dealing with a VANET there are some characteristics to consider beyond the type of communication such as:

- **Highly dynamic topology:** VANET networks due to the speed of the nodes and range of the radio signal that is mainly dependent on radio wave frequency used.
- **Frequently disconnected:** Since the nodes are highly dynamic, those can be in and out of range in a matter of seconds due to variation of speeds, causing frequently changes on the state of the connection between nodes and updates on the routing tables of each node.
- **Geographical position and patterns:** In case of some routing protocols, in particular the geographic based that which will be explained forwarder, can benefit from geographical information in order to predict mobility pattern for future routing purposes.
- **Propagation model:** For most of cases, VANETs operate in three environments such as urban scenarios, highways and rural. Therefore, a network has to be able to adapt the propagation models between each environment, since it is known that rural areas are not as dense a urban areas. Where the signal can suffer from interference and reflections, or even total loss of signal due to blocking by the buildings.

Therefore, there are spatial and temporal constraints with this kind of network whereas fixed network don't and that need to be taken into account to the design of communication protocols in VANETs.

2) VANET protocol stack: The protocol stack for vehicular networks has to manage communication with nearby vehicles and between them, pedestrians and roadside equipment as previous mentioned. Therefore there is a protocol stack designed to handle all the challenges mostly based on the IEEE 802.11 Wireless Access in Vehic-ular Environments (WAVE) standards [4] as illustrated in the Fig. 1 [5].

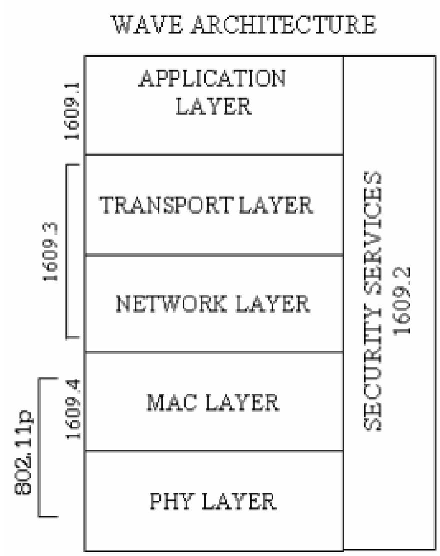

Fig. 1. WAVE protocol stack

3) Physical layer: The physical layer in vehicular networks is a challenging one compared with our typical fixed topology networks. For instance, the protocols in this layer must take into account the multipath fading as well Doppler effect in radio wave frequencies shifts caused by the fast movements of the nodes specially in highway scenarios. Vehicle-to-vehicle communication have use radio wave usually on very high frequencies [6], for instance micro and even millimeter waves which are also used in 5G, are used. Note that millimeter waves are only used in line-of-sight communication, whereas the microwaves are used in the broadcast type communications. The frequencies used, were defined in the Dedicated Short-Range Communication (DSRC) system which is dedicated to VANETs. This system is as the name suggest is a short to medium range communication technology that operates around the 5.9GHz band. In which, according to the European Telecommunications Standards Institute (ETSI), 70 MHz where allocated so it operates in the 5.885-5.925 Ghz band. The DSRC system is able to manage speeds up to 200km/h, and a transmission range up to 1000m. In addition, the DSRC is known as the IEEE 802.11p WAVE standards where it also defines the function and services that operate in vehicular networks without the need of a Basic Service Set (BSS), which means that no common AP is needed in the network to provide communication between nodes. The IEEE 802.11p also defines interfaces functions between the physical layer and the MAC layer, sharing the same logical channel as we can see in the Fig. 1 as well as the other DSRC channels, each with represent with the IEEE 1609 standards which are divided by the following list from the article [6], [7]:

- **1609.1:** Specifies the services and interfaces of the WAVE Resource Manager application.
- **1609.2:** Defines secure message formats and processing.
- **1609.3:** Defines network and transport layer services including addressing and routing, in support of secure WAVE data exchange.
- **1609.4:** Enables operation of upper layers across multiple channels, without requiring knowledge of PHY parameters.
- **802.11p:** Define the WAVE signaling technique and interface functions that are controlled by the IEEE 802.11 MAC.

Also according to the ETSI and In the Fig. 2, the frequency band is divided into six service channels (SCH) and one control channel (CCH), each one with a band of 10 MHz and all of them filling the 70 Mhz band allocated previously mentioned to the DSRC. Each channel is allocated to three types of applications. The ITS non-safety 5.855-5.875 MHz, safety, and traffic efficiency 5.875-5.905 Mhz, Future ITS 5.905-5.925 Mhz [8], [9] .

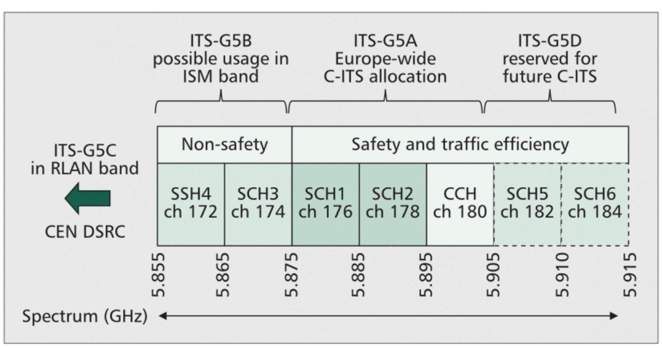

Fig. 2. Channels in vehicular networks according to the IEEE 802.11p standards [10]

4) MAC layer: Media Access Control (MAC) layer protocols are responsible for managing the use of a share medium, therefore these protocols decide which nodes will access the medium at any given time. The MAC layer in case of vehicular networks has to provide a reliable, stable and efficient channel. Also, MAC protocols should consider the different applications for which the communication will occur. For example, messages related with safety applications have to be sent rapidly, with low failure rate. Therefore, this calls for a resilient medium of communication, which is even more challenging when dealing with VANETs due to the highly node mobility and topology changes. And this is especially important since with the 5G capabilities the trend is to use even more multimedia applications by passengers, demanding more throughput in the VANET network. In addition, in VANETs, the bandwidth has to be shared between vehicles, that being said, the use of Orthogonal Frequency Division Multiplexing (OFDM) technology to control the medium access communication to avoid collisions. Fortunately, the IEEE 802.11p WAVE protocol is designed to fulfill the requirements present in V2X communications, where high reliability and low latency are are mandatory. This is done by enabling a very efficient communication setup with little overhead and removing the BSS operations from the IEEE 802.11 in a truly ad hoc environment for vehicles [7].

5) Network layer: The network layer, the layer that allows for the connection and transfer of data packets between the nodes by using routing protocols that implement viable ways of communication without disruption. With that said, in vehicular networks it supports different communications:

- **Unicast communication:** Type of communication from the source node to target node end-to-end in the network via multi-hoping. Where the target node may be at a known location or within a certain range. Despite this communication usefulness in VANETs, multicast is better suited for applications that require dissemination of messages to different nodes in the network.
- **Multicast/Geocast communication:** Type of communication, where the data transmission is addressed to a group of targets simultaneously. Geocast is based on the Multicast but takes into account the geographical location into the mix. In which a message is sent to a group of targets node based on their geographic position, commonly based by the relative distance to the source of the message.
- **Broadcast communication:** Type of communication, where the source node sends data to everyone on the network at once. However, in vehicle networks the broadcast works a little bit differently from the typical fixed networks. In these networks, the nodes are scattered in the space, which means that. Probably in most of the cases, the nodes may not be within the range transmission of the source node. To prevent this, the target nodes from the first source, relay the data also in broadcast mode repeating the process until no nodes are within range of the source. Forming a chain of broadcast messages that breaks when no vehicles are in range. In addition, it is with broadcast that the nodes discover their neighbours in the discovery phase of the routing protocols in order to find the most efficient route for the unicast communications.

With mention of routing protocols, it is to note that routing protocols are very different from the typical fixed networks and since there are some substantial differences. With that said, the routing protocols will have their own section II-B dedicated to them ahead, despite their operation in this section of network layer.

B. Routing Protocols

Due to the high mobility of nodes in a VANET environment, designing routing protocols able to compute and handle efficiently many routing paths among vehicles, represents nowadays a challenging research issue. Until now, several routing protocols have been developed, some of them have been adaptations improving already established algorithms from MANETs. However, this protocols despite having been demonstrated on how they can perform well for MANETs, that does not mean that they are able to guarantee the same level of efficiency into VANETs scenarios. And, that is why new approaches and more sophisticated strategies have been developed where a lot of this approaches manages the routes starting from the information about the node location where other protocols group the nodes into smaller clusters [11].

Being said that , the rest of this section is dedicated to a summary of the most know VANETs routing protocols that can be divided in five different categories [12]: Topology-based, Broadcast, Cluster-based, Position-based and Infrastructure-based.

1) Topology-based Ad-hoc Routing Protocols: In this category of routing protocols there are some algorithms that have been designed for MANETs and have been adjusted to fit a VANET environment. Topology-based protocols can be divided in categories, proactive, reactive and hybrid which is a mix of both.

- **Proactive:** In this type of routing protocol, each node on the network keeps on maintaining regularly the routing table to store the routes information for every other node. Therefore, each table entry contains the information of the next-hop, despite the route being needed or not by using the Bellman Ford Algorithm. Since we are in a VANET environment, this tables must be updates regularly to reflect the topology changes of the network, and to perform that each node has to broadcast regularly to discover its neighbours. However, this has a downside, it produces overhead cost due to maintaining up-to-date information and as a result it may affect the throughput of the network. Upside is that whenever is necessary, it has the availability information of the next-hops. Also, the proactive routing protocols relies on the shortest path algorithm to find out the optimum route, for that there are two kind of strategies, link state strategy and distance vector strategy.
- **Reactive:** In this type of routing protocol, each node on the network keeps on maintaining only the routes in need. Therefore, each node starts a route discovery process when it wants to send data if the path is not already known. This network paths searching, relies on handshake by flooding route request messages and it reaches the destination node, the destination node replies in unicast communication forming a connection. That means that reactive protocols are more suited for dense networks, high mobility that frequently change typologies die to the reduce overhead of maintaining the routing tables of the proactive protocols.

2) AODV: AODV protocol stands for ad hoc on-demand distance vector routing protocol. Which is a reactive protocol that enables dynamic, self-starting, multihop routing between nodes wishing to establish and maintain an ad hoc network. Since it is a reactive protocol and allows nodes to obtain routes quickly for new destinations and does not require nodes to maintain routes to destinations that are not in active in communications. Doing all this while dealing with link breakages and changes in network topology in an acceptable time window since when a link breaks, this protocol notifies the affected set of nodes by sending a route error message, so that they can invalidate the routes using the lost link quickly. Also, the operation of AODV protocol is loop-free, and by avoiding the Bellman-Ford ”counting to infinity”. And does that by using a simple solution and a distinguishing feature of this protocol which is the use of a destination sequence number for each route entry. In addition, the AODV protocol uses the UDP transport protocol to send its own messages that are mostly Route Requests (RREQs), Route Replies (RREPs), and Route Errors (RERRs).

3) OLSR: OLSR protocol stands for Optimized Link State Routing protocol. Which is a proactive protocol, meaning that is a routing table driven protocol that exchanges and manage topology information regularly between nodes of the network. To do that, each node selects a set of neighbours nodes as multipoint relays (MPR), these nodes are responsible for forwarding the control traffic, intended for diffusion into the whole network. MPRs provides an efficient mechanism for flooding control traffic by reducing the number of transmissions required. Another responsibility of the nodes selected as MPRs, is to declare all the link state information in the network periodically over the control messages in order to OLSR maintain the shortest paths routes updated and for redundancy. In addition, in route calculations, the MPRs are used to form the route from a source target to any destination in the network.

4) DSDV: DSDV protocol stands for destination sequence distance vector routing protocol. Which is a proactive protocol, meaning that is a routing table driven protocol based on the distance vector strategy and applies the shortest patch algorithm of Bellman-Ford. In this protocol only one optimal route is stored in the routing table for each destination while having the information to all approachable network’s nodes with the destination nodes and its costs. Similarly, to the AODV , this protocol also stores as a label the sequence number of its routes in order to avoid the Bellman-Ford ”counting to infinity” problem. DSDV maintains the routes by periodically broadcasting the control messages to its neighbours. Since DSDV is a proactive protocol, it is more prone to overhead with the increase number of nodes due to the addition overhead to maintain the routing tables. However, the main limitation of DSDV routing protocol is that lacks congestion control for the network, multiple paths for destinations decreases the DSDV routing efficiency. These limitations were mitigated with a new protocol based on the DSDV, the Randomized-DSDV. Which provides support for network congestion control, but with that also having an increase of overhead compared to DSDV.

C. Broadcast Routing Protocols

In general, the role of a protocol is to find a route to connect two nodes. However, routing algorithms based on broadcast protocols have a different aim. This kind of protocols are used whenever the destination node is out of the range of the source node. Mostly these protocols are used with application that are concerned with the safety such as road and weather condition warning, emergency warning messages, road conditions among others, where the information is use full to every node. The positive side of these kind of protocols is the reliability, therefore being used for safety. The downside is that these types of protocols consume more bandwidth, and many duplicate packets reaches the node which is not an efficient use of resources.

D. Cluster-based Routing Protocols

As said previously, in VANETs the topology changes are very frequent over, usually large areas. Therefore, dealing with scalability is usually a big issue. One way of dealing with that issue is by diving the network in different regions or clusters, which coordinate and communicate with each other to achieve communications between nodes. Moreover, if a vehicle node needs to communicate with another node within the cluster then the communication is a direct path as it is considered to be a local communication. If the vehicle node needs to communicate with another node outside the cluster then it requires the help of its cluster head for reaching the destination. The positive side of cluster-based protocols are the scalability factors as it makes a good choice for complex networks over large areas. However, the drawbacks are traffic delays.

E. Position-based Routing Protocols

In these kinds of protocols, a source node will communicate to the destination node using by using geographical positions as well as with its network address. The geographical position of the nodes, can be obtained naturally trough GPS or V2I communication since it is know the location of the Roda Side Unit (RSU) infrastructure [13] that can act as redundancy whenever the satellite signals is weak when the vehicle goes in the area like tunnel. In the position-based routing protocols there is a specific category, Geocast routing, in which the nodes are being the nodes are being divided into predefined geographical positions regions. And, to forward the packets there are three strategies: 1) Greedy forwarding 2) Restricted directional flooding 3) Hierarchical.

Since position-based protocols use geographical location information of the nodes within the network. In a vehicular scenario such as VANETs, movements are usually restricted in a few directions based on the road network, therefore having an advantage of predictability and performance over other routing protocols designed for VANETs. Hence, position-based protocols being nowadays the most promising protocols for VANETs scenarios.

F. Infrastructure-based Routing Protocols

As said previously in the position-based routing protocols II-B1, the use of road side infrastructure can be used as redundancy whenever the satellite signals is weak. However, in infrastructure-based routing protocols instead of being used as redundancy is the main source of information relying on fixed infrastructure bases to assist routing issues.

G. NS-3 Introduction

NS-3 or network simulation 3 is a discrete event network simulator successor of NS-2, intend to focus primarily on research and educational use as it is a free software, licensed under the GNU General Public License version 2 [14]. Therefore, license was created in order to guarantee the freedom to share or modify the software which is relevant for any researcher that intends to use and modify the NS-3 for his research.

H. SUMO Introduction

SUMO or Simulation of Urban Mobility is a free and open-source vehicular traffic simulation intend to focus primarily on research, and both educational and commercial purposes. SUMO is mainly developed by the employees of the Institute of Transportation Systems at the German Aerospace Center and licensed under the Eclipse public license V2. Which means this license guarantee the freedom to share or modify the software as long as the contributor or distributor provides it as an open source. It is available since 2001 and it allows modelling of intermodal traffic systems, this means that it allows modelling of road vehicles, public transport, and pedestrians. Also, included with SUMO is an extent of numerous supporting tools which intend to automate core tasks for the creation, the execution and evaluation of traffic simulations, such as network import, route calculations, visualization, and emission calculation.

III. SUMO&NS3 Coupling

This section is related to the contribution of this thesis, the SUMO&NS3-Coupling tool software that is the main tool that couples this SUMO and NS-3 software in order to produce useful data for study routing protocols for VANETs. So, in diving into the process of how to use the tool starting with the creation of a vehicular mobility scenario with the SUMO simulator until the moment the simulation output data is generated. All the material develop and generated with the SUMO&NS3-Coupling are provided through a GitLab repository for thesis in the following link: https://gitlab.com/ist-ricardo-santos/performance-analysis-of-routing-protocols-on-vanets since, most of the material used for this thesis are very extensible and cannot be attached directly to this document.

A. SUMO&NS3-Coupling Architecture

The SUMO&NS3-Coupling tool allows anyone to combine two programs SUMO and NS3 in order to achieve realistic mobility scenarios for VANET routing protocols study. And does it by making a process of various steps done sequentially and seamlessly to the user. The process can be divided in four phases, listed below and as we can see in the Fig. 15 in the appendix.

- **Vehicular Mobility Scenario Creation:** This is the initial phase, where we create the mobility scenarios. The SUMO simulator so that we have the mobility files needed to start with the SUMO&NS3-Coupling.
- **SUMO&NS3-Coupling Translation:** This is the Second phase, where the user input the mobility files to the SUMO&NS3-Coupling tool so that the program can do its job until outputting all the result. In this phase, the program takes the mobility files input, parses them, and automatically creates new files that the NS3 can ingest, it is like a translation process from SUMO to NS3.
- **NS3 Simulation:** This is the third phase, where the NS3 simulator takes the translated mobility files and starts the network traffic simulation with the different routing protocols such as AODV, OLSR and DSDV running in a WAVE environment. After all the runs with the different simulators output data is generated, and that data goes back to the SUMO&NS3-Coupling.
- **SUMO&NS3-Coupling Results:** This is the final phase, and this phase is where the SUMO&NS3-Coupling takes the output of the NS3 simulator which are mostly .csv data and automatically, does a statistical work on the data, also generates graphs to visualize better the KPIs of the simulated scenarios.

B. Vehicular Mobility Scenario Creation

As previous mention in the previous section, SUMO is an urban mobility simulation program which provides tools for creating vehicular mobility scenarios. Therefore, for the experimental environment we will use it to create the mobility scenarios using the Netedit tool included in SUMO.

From this point onwards, it is required to create a mobility scenario with the aid of SUMO. Once the mobility scenarios are completed, we can analyze the output files which are mainly `.xml` files and the most important one the `.sumocfg`, this is the file that will be served as input for the SUMO&NS3-Coupling tool. These files contain the information about the scenario, containing all the information about edges which are roads in SUMO, lanes, junctions, connections, traffic intensity, traffic type and more.

That being said, in order to continue the rest of the experimental process we need to have at least the following files listed below:

- **mobilityScenario.sumocfg:** This is the main file that will be used for the rest of the process. Is the configuration file which invokes the `.xml` files detaining all the detail about the scenario as we can see below.
- **mobilityScenario.net.xml** This file has the information about vehicular road network, it contains all the details such of id's, coordinates, speeds and lengths of the edges, lanes, junctions, and connections. As we can see bellow on the `.xml` code, the edge: `gneE1` has a speed of 13.89m/s which is about 50km/h and the lane length which is 89.60m. We can also see an example of a junction and connection where the edge is involved:
- **mobilityScenario.rou.xml or mobilityScenario.trips.xml:** This file has the information about the vehicular traffic on the road network, it contains the routes of each means of transport, such as cars, buses, trains, taxis, trucks, bicycles, motorcycles among others. In this file, we can have two types of routes, trips, and flows. The trips represent only one vehicle, and the flows represent multiple ones depending on the number attribute. For instance, on the listing bellow, we can see those two types, the trip, and the flow. Note that on the flow we have the number at 180, begin at 0, and end at 1800. This means that for 1800 seconds we will have 180 vehicles, which is the departure rate of 1 vehicle per 10 seconds.

Again, note that the scenario can have more files than the ones motioned depending on the complexity of the mobility scenario, for instance if it includes POI, buildings, public transportation among others and still proceed with experimental process. But again, only the listed above are mandatory since these are the ones that the SUMO&NS3-Coupling tool needs to generate the file that is needed to proceed to the NS3 phase with the purpose to utilize the vehicular mobility to study the various routing protocols.

For this thesis study, four different scenarios listed below were created with different characteristics examine the vehicular network routing protocols and V2X communications.

- **Urban Grid Scenario:** Aims to represent a scenario which is commonly has more node density with lower vehicular speeds.

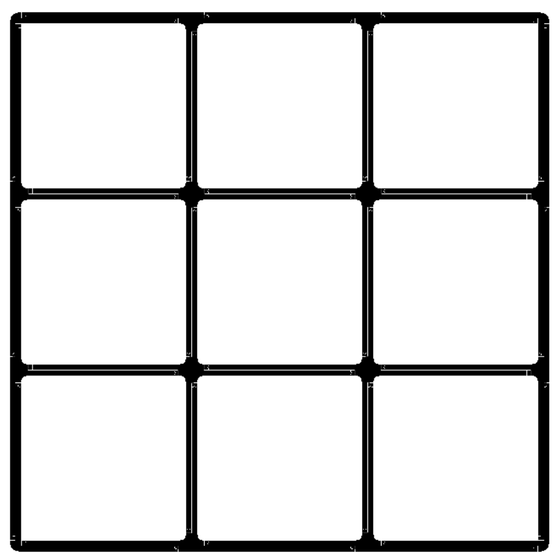

Fig. 3. Grid map

- **Highway Scenario:** Aims to represent a scenario with higher vehicular speeds.
- **Country Grid Scenario:** Aims to represent a scenario usually has less node density with lower vehicular speeds.
- **Realistic Scenario:** Aims to represent a more realistic scenario, with a snapshot of Lisbon map similarly to a

Fig. 4. Highway map

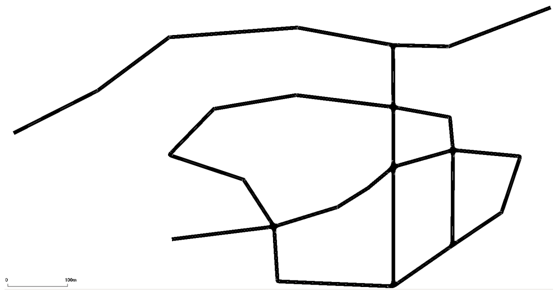

Fig. 5. Country map

GPS application commonly used in smartphones.

Fig. 6. Lisbon map

TABLE I
MOBILITY SCENARIOS CHARACTERISTICS

Scenario	Grid	Highway	Country	Lisbon
Node number	50	40	21	62
Road Length	4.17 km	6 km	7 km	67 km
Average Speed	33.2 Km/h	90 Km/h	49 Km/h	23 Km/h
Simulation time	219s	100s	174s	656s

C. SUMO&NS3-Coupling Translation

This is the Second phase, where the user input the mobility files to the SUMO&NS3-Coupling tool so that the program can do its job until outputting all the result. In this phase, the program takes the mobility files input, parses them, and automatically creates new files that the NS3 can ingest, it is like a translation process from SUMO to NS3

It is in this phase where we run SUMO&NS3-Coupling program. However, as previously said to continue with the simulation process is necessary to have the right files, more in particular the `mobility Scenario.sumocfg` which is the input file.

Being said that, to start the SUMO&NS3-Coupling program, type the following command on `/tese` directory with all the material provided:

```
source Simulation.sh
    SUMO/mobilityScenario/
    mobilityScenario.sumocfg
```

After typing the command, the simulation can take a while depending on the complexity of the mobility scenario, for instance the Realistic Scenario took four hours on a modern high-end laptop. Again, it could not be simpler, it just requires typing a single command and then the user can leave the computer for hours to come back with all the results.

Then the SUMO&NS3-Coupling program will initiate the first action, converting the `mobilityScenario.sumocfg` into a trace file `mobilityScenario.xml`. This file is a file sorted by time in seconds with the of the vehicles' information or flows in the given second as we can see below:

However, this `mobilityScenario.xml` file is not yet compatible with the NS3. So, the second action of the SUMO&NS3-Coupling program is to convert the `mobilityScenario.xml` into a `mobilityScenario.tcl`. This file narrows down the `mobilityScenario.xml` to the essential information about the mobility of the vehicles for the NS3 simulator, by running the `traceExporter.py` python code resulting in a file sorted again by time in seconds with x,y,z axis information of each vehicle in the given second as we can see below. That way the NS3 can parse the file in order while changing the node positions in the VANET simulation.

Now that the `mobilityScenario.tcl` file is ready to enter the NS3 simulation, but to run a NS3 simulation there are other input parameters that are needed such as time of simulation, number of nodes, protocols, among others. So, to avoid making the user do all that manually, which can be complex and time consuming depending on the complexity of the `mobilityScenario.tcl`, the `TclParser.py` will handle the time of simulation and number of nodes. Then the SUMO&NS3-Coupling program will start to invoke multiple runs of the mobility scenario in NS3, which will be explained better in the next section.

D. NS3 Simulation

This is the third phase, where the SUMO&NS3-Coupling tool sets up NS3 simulation runs for the mobility scenario chosen. The way the SUMO&NS3-Coupling is programmed makes it run four simulations of the `vanet-routing-compare.cc` which is a code inspired in the `manet-routing-compare.cc` with that takes advantage of multiple modules, and one of them is the Ns2Mobility helper, imported from the predecessor of the NS3, the NS2. This module is responsible for taking the mobility trace `mobilityScenario.tcl`, returning the position of each node every second of the simulation. Another module used which and the main one is the WAVE helper, which is responsible for performing the WAVE protocol. Also, many other modules were used, for instance the routing protocols helpers for the OLSR, AODV, DSDV and DSR.

With that said, in the four different simulations runs, each will have a different VANET routing protocols in the following order and sequentially, OLSR, AODV, DSDV and DSR. After each run the SUMO&NS3-Coupling will create a new directory on the mobility scenario directory called `Stats`, the Again, the user do not need to worry about setting up any of this, the tool will handle everything, and this process can take a while depending on the complexity, particularly with the increase of the number of nodes is the one that impacts that aspect the heaviest so we need to be careful setting it up according to our machine's computational power.

E. SUMO&NS3-Coupling Results

As said previously on the NS3 Simulation section, after each simulation the SUMO&NS3-Coupling creates a new directory called `Stats`. This is the directory where every possible outcome of the SUMO&NS3-Coupling tool is stored after each simulation run of every routing protocol, starting with the OLSR simulations first, then AODV, DSDV and finally DSR. Therefore, after each simulation is completed a new directory with the name of the protocol of whose simulation run has just finished where all the data files associated to that run are stored. Those files can be the following:

- **mobilityScenario_mobility_NetAnim.xml:** This file, contains the information about each node ID, IP in the network, geographical position as well as the messages sent and received. And this file that can be used by a NS3 tool which is the NetAnim tool, which is a tool that provides a graphical view of the behavior of the VANET mobility scenario.
- **mobilityScenario_mobility_stats.csv:** It is in this file where statistical information about each simulation run, for instance receive rate, packets received, wave packets sent or received, MAC overhead among others as we can see below:
- **mobilityScenario_mobility_routing_table:** As the name suggests this file contains the routing tables of each node.
- **mobilityScenario_mobility_FlowMonior.xml:** This file contains information on the flows of the messages between nodes, such as delays, packets sent and received, bytes sent and received and jitter among others.
- **mobilityScenario.log & mobilityScenario.mob:** These files contains information about the geographical position of the nodes as well as their id's and velocity. At the moment theses files are not used, but eventually they can be in the case of future work on the SUMO&NS3-Coupling tool.

After the SUMO&NS3-Coupling tool has run the four runs of each routing protocol, it will parse each one of the `mobilityScenario_mobility_stats.csv` files and plot graphs in order to visualize better the performance comparison between protocols. And does it by using the gnuplot which is a command-line driven graphing utility for Linux. More on this, in the next section which will be focused on the comparisons of the routing protocols. In addition, there is a python code `flowmon-parse-results.py` used to extract statistical information from the `mobilityScenario_mobility_FlowMonior.xml`.

The SUMO&NS3-Coupling tool plots 20 graphs with different metrics per routing protocol used in each mobility scenario. However only a portion of those metrics are useful for performance comparison [15], [16], [17], those are the receive rate resembling the goodput in packets per second and the overhead caused by each protocol represented by the portion of every packet from the routing protocol sent by the total of packets sent in the network. As we can see in from the line of code in the `vanet-routing-compare.cc` code below. The overhead metric is the main metric of comparison since this metric unveils the extra bandwidth consumed by overhead to deliver data traffic.

Also, to provide more context to the analysis, the average speed in meters per second and the number of running vehicles in a particular second of the simulation. With that said, the following sections are dedicated to each mobility scenario where we can see the output with the comparisons of the SUMO&NS3-Coupling tool to each routing protocol.

1) Urban Grid Scenario: The urban scenario, as said previously aims to represent a scenario which commonly has more node density in this case reaching a peak of 34 nodes for a couple of seconds, also every node is within a square kilometer since every edge of this grid is 100m, therefore making it 300x300m Fig. 3. In this grid mobility scenario, the nodes are circulating at speeds ranging between 6-12 meters per second which is about 20-40 kilometers per hour. In these circumstances, we can see that in from the graph in the figures 7,8 and table II that the receive rate is similar between protocols, however the OLSR protocol has a slightly advantage of 2.6% over the AODV and 4.4% over the DSDV. On top of that advantage, the overhead caused by the OLSR protocol is lower compared to AODV and DSDV with a difference of -33.7% and -10.2% respectively. This means that, for the OLSR protocol uses less packets, 39.6%, to maintain all the communication necessary between nodes. Having said that, is clear that the OLSR routing protocol performs better than the other protocols in the urban mobility scenario.

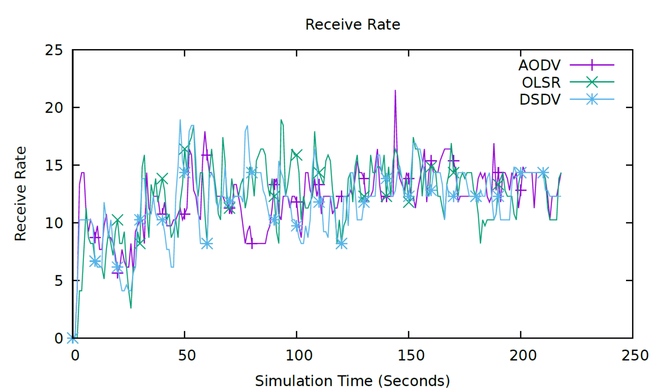

Fig. 7. Receive Rate Grid Scenario

2) Highway Scenario: The highway scenario, as said previously aims to represent a scenario which commonly has high node mobility speeds, in this case the are circulating with an average speed of 25 m/s which is about 90 kilometers per hour. Also, the number of vehicles running at a certain second in

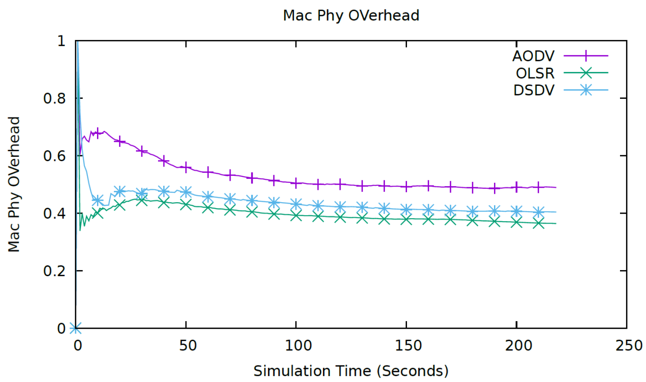

Fig. 8. Overhead Grid Scenario

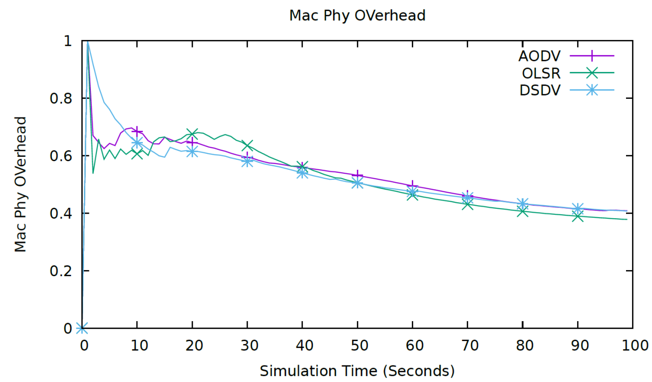

Fig. 10. Overhead Highway Scenario

TABLE II
METRIC AVERAGES OF GRID SCENARIO

Protocol	Receive Rate	Overhead
AODV	12.109	0.530
OLSR	12.433	0.396
DSDV	11.906	0.437

TABLE III
METRIC AVERAGES OF HIGHWAY SCENARIO

Protocol	Receive Rate	Overhead
AODV	9.923	0.530
OLSR	9.308	0.516
DSDV	10.173	0.525

the simulation reaches a peak of 34 nodes at the second 57, and every node is within a area of 1000x200m Fig. 4. In these circumstances, we can see that in from the graph in the figures 9,10 and table III that the receive rate is similar between protocols. Also, we can see a interesting phenomenon, in the receiving rate graph, that durint the time period between the 20 seconds and 50 seconds the rate is very low when comparing the same time period in the running vehicles graph which is high. This can be counter intuitive, however, the reason is that many vehicles are far away from each other and not making as many communications. In addition, we can verify that the DSDV protocol has a advantage of 2.3% over the AODV and 9.3% over the OLSR. On top of that, the overhead caused by the DSDV protocol is slightly lower compared to AODV and higher compared to OLSR with a difference of -1.0% and 1.9% respectively. Having said that, is clear that the DSDV routing protocol performs better than the other protocols in the highway mobility scenario.

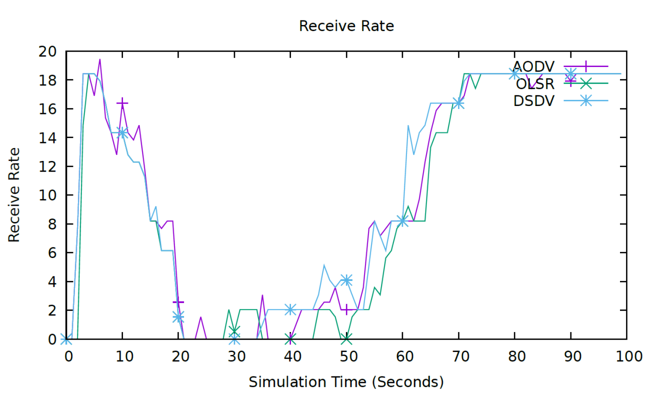

Fig. 9. Receive Rate Highway Scenario

3) Country Scenario: The country scenario, as said previously aims to represent a scenario which commonly has low node density in this case reaching a peak of 34 nodes at the second 54 in the simulation. However, unlike the grid scenario the country scenario has an area much bigger of 900x300m Fig. 5, therefore less dense. In this country mobility scenario, the nodes are circulating at speeds ranging around the 15 meters per second which is about 54 kilometers per hour. In these circumstances, we can see that in from the graph in the figure 12 and table IV that the receive rate of the DSDV protocol has a slightly advantage of 5.2% over the AODV and 19.2% over the DSDV. However, the overhead caused by the DSDV protocol is the highest of the three. If we consider the AODV protocol in this metric, the protocol compared to OLSR and DSDV has a difference of -6.6% and -23.3% respectively. A difference of 23.3% is a very considerable one, and since the advantage of DSDV over the AODV in the metric rate is only 5.2%, it is safe to assume that the AODV protocol is the most suited protocol in the country scenario for most use cases. However, if the goodput is extremely needed over other metrics, the DSDV is the best option.

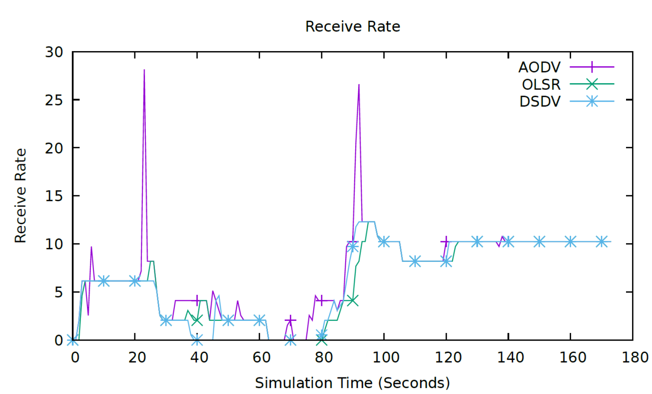

Fig. 11. Receive Rate Country Scenario

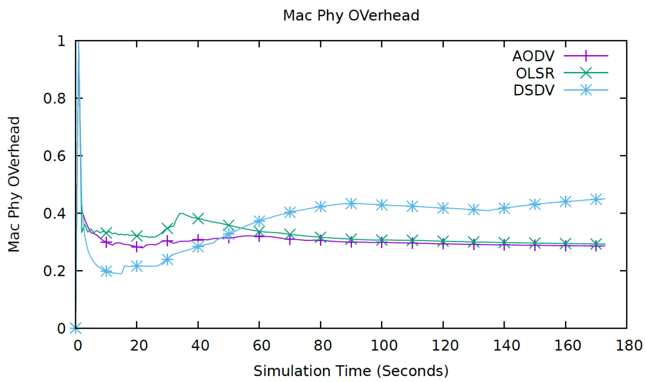

Fig. 12. Overhead Country Scenario

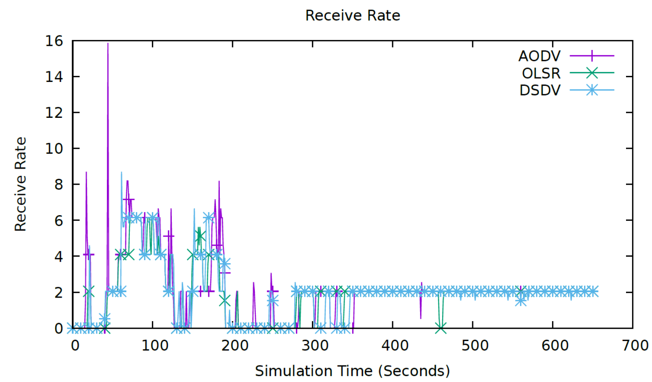

Fig. 13. Receive Rate Lisbon Scenario

TABLE IV
METRIC AVERAGES OF COUNTRY SCENARIO

Protocol	Receive Rate	Overhead
AODV	7.039	0.300
OLSR	6.309	0.320
DSDV	7.403	0.370

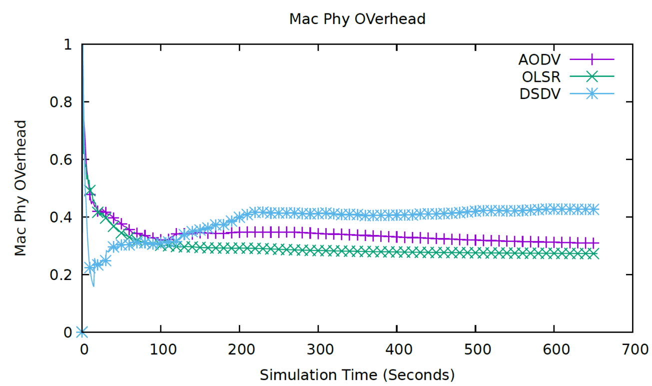

Fig. 14. Overhead Lisbon Scenario

4) Lisbon Scenario: The Lisbon scenario, as said previously aims to represent a a more realistic scenario, with a snapshot of Lisbon map. This portion of the Lisbon city is called the "Baixa de Lisboa", meaning the lowest zone of Lisbon. And, in this scenario the number of vehicles running at a certain second in the simulation reaches a peak of 58 nodes for a couple of seconds as we can see in the Fig. 13, also every node is within an area of 1500x700m Fig. 6. In this grid mobility scenario, the nodes are circulating at speeds ranging between 0-16 meters per second with an average of 5 m/s which is about 19 kilometers per hour as we can see in the table I. In these circumstances, we can see that in from the graph in the figures 13,14 and table V that the receive rate is similar between protocols, however the AODV protocol has a slightly advantage of 6.5% over the OLSR and 4.9% over the DSDV. In terms of overhead, the OLSR protocol has the lowest when compared to AODV and DSDV with a difference of -14.9% and -31.1% respectively. Having said that, despite the OLSR performing slightly worse in terms of goodput, overall is clear that the OLSR routing protocol performs better than the other protocols when considering the overhead caused by the other protocols in the Lisbon mobility scenario. Making the OLSR the best option for this scenario.

TABLE V
METRIC AVERAGES OF LISBON SCENARIO

Protocol	Receive Rate	Overhead
AODV	2.034	0.340
OLSR	1.910	0.296
DSDV	1.939	0.388

IV. CONCLUSIONS & FUTURE WORK

A. Conclusions

This thesis addressed an emerging field in the future of ITS, that is VANETs. More precisely, the routing protocol side of VANETs by testing the performance of three topology-based routing protocols in VANETs which are AODV, OLSR and DSDV. The testing was executed with the aid of the SUMO&NS3-Coupling tool developed in this thesis, enabling us to test four different mobility scenarios settings such as urban, highway, countryside and finally a realistic scenario resembling a famous area of Lisbon. Utilizing the SUMO&NS3-Coupling tool for the testing and judging it mostly with the overhead and goodput metrics of each protocol, in these circumstances, the urban and Lisbon scenarios were those where the OLSR was the clear winner over the others making it more suited for high node density scenarios. Furthermore, in settings with high speeds of mobility such as highway scenarios the DSDV routing protocol outperforms AODV and DSDV having the best ratio between the goodput and the overhead caused between the three protocols. Finally, in the countryside scenario, aimed to test the protocols in a low node density ambient, the AODV outperformed the DSDV, however, the same cannot be said for the OLSR that clearly struggled in this type of scenario. All things considered, this thesis concludes that the OLSR routing protocol is the most adequate for the majority of the scenarios, specially the ones with high node density, performing better in tow out of four scenarios, not trailing too much behind in the highway scenario, and lacking in the rural scenario where the low node density has affected negatively the OLSR when comparing the goodput with the overhead caused against the other protocols.

B. Future Work

The SUMO&NS3-Coupling very flexible, therefore making it very easily modifiable, so anything that improves or adds new functionalities to the SUMO&NS3-Coupling could be done. For instance the addition of new routing protocols such as position-based routing protocols with are probably the most adequate protocols in a near future for this kind of networks. Also, the addition of new and improved metrics for the current simulations. And for more ambitious ideias, the inclusion of autonomous vehicles data or video streaming data into the packets of the simulations. That being said, the SUMO&NS3-Coupling tool is the perfect foundation for future ideas and work related with VANETs and enables anyone who desires to work with VANETs to build on it.

Acknowledgment

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Appendix
SUMO&NS3-Coupling Architecture

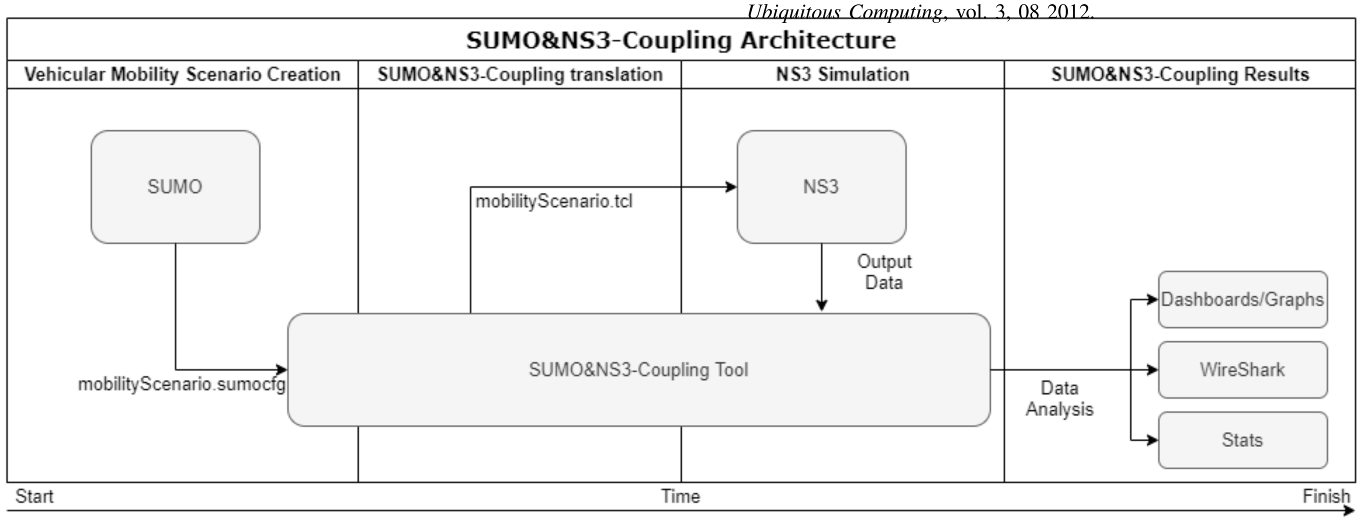

Fig. 15. SUMO&NS3-Coupling Architecture

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