Universidade de Aveiro
Departamento de Electrónica, Telecomunicações e Informática
2013

Diogo Emanuel Silva Jordão Carreira

Mobilidade de Comunicações entre Veículos e Infraestrutura

Mobility of Communications between Vehicles and Infrastructure

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'Dedico este trabalho aos meus Pais pela sua presença'

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Dissertação apresentada à Universidade de Aveiro para cumprimento dos requesitos necessários à obtenção do grau de Mestre em Engenharia Electrónica e Telecomunicações, realizada sob a orientação científica da Professora Doutora Susana Isabel Barreto de Miranda Sargento do Departamento de Electrónica, Telecomunicações e Informática da Universidade de Aveiro, e do Professor Doutor João Barros do Departamento de Engenharia Electrotécnica e de Computadores da Faculdade de Engenharia da Universidade do Porto.

o júri

Presidente

Prof. Doutor José Alberto Fonseca
Professor Associado do Departamento de Engenharia Electrónica, Telecomunicações e Informática da Universidade de Aveiro

Orientadora

Prof. Doutora Susana Sargento
Professora Auxiliar do Departamento de Engenharia Electrónica, Telecomunicações e Informática da Universidade de Aveiro

Coorientador

Prof. Doutor João Barros
Professor Associado do Departamento de Engenharia Electrotécnica e de Computadores da Faculdade de Engenharia da Universidade do Porto

Arguente

Prof. Doutora Ana Aguiar
Professora Auxiliar Convidada, do Departamento de Engenharia Electrotécnica e de Computadores da Faculdade de Engenharia da Universidade do Porto

agradecimentos

Agradeço à minha família, nomeadamente aos meus pais pelo incansável apoio, desde cedo, neste meu percurso académico. Quero agradecer também aos meus amigos e namorada, pois sempre estiveram presentes nos momentos mais difíceis. Um especial agradecimento à Professora e presente orientadora Susana Sargento, por ter acreditado em mim desde o início. Finalmente, gostaria de expressar a minha gratidão àqueles que me ajudaram no desenvolvimento da Dissertação, em especial ao André Cardote.

Palavras-Chave

VANET, Handover, IEEE 802.11p, AHP, Gestor de Conectividade, Algoritmo Genético, Infraestrutura

Resumo

As características únicas das redes veiculares, como a elevada mobilidade, a topologia dinâmica e a frequente perda de conectividade, tornam o esquema da escolha de rede num problema complexo. Num ambiente replecto de redes sem fios, principalmente nas áreas urbanas, existe um aglomerado e sobreposição de várias redes e tecnologias. Assim, para garantir ao utilizador a conectividade de forma transparente, é necessário a presença de um mecanismo capaz de tomar decisões informadas. Com o aumento do tráfego móvel, várias iniciativas estão a ser realizadas, disponibilizando hotspots IEEE 802.11 a/g/n (Wi-Fi) pelas cidades, de forma a retirar tráfego das redes celulares. Por um lado, os clientes podem usufruir de preços mais baixos e por outro lado, os operadores conseguem reduzir a quantidade de tráfego móvel. Além disso, os utilizadores irão preferir ligar-se a uma rede mais barata/grátis sempre que estiver disponível, desde que tenha boa qualidade. Uma vez que nas redes veiculares os nós são veículos, as redes disponíveis estão sempre a mudar, tornando-se cada vez mais instáveis com o aumento da velocidade. Assim, a mobilidade dos nós põe em causa as soluções existentes para mecanismos de selecção de redes, que maioritariamente para elegerem a melhor rede se baseiam apenas na qualidade do sinal. Além disso, para um ambiente de redes veiculares, não existem mecanismos de selecção capazes de ter em conta comunicação Vehicle-to-Vehicle (V2V) de acordo com a tecnologia Wireless Access in Vehicular Environments (WAVE) / (Dedicated Short-Range Communications (DSRC). Assim, é proposta a criação de um gestor de conectividade capaz de ter em conta determinados factores que se encontram disponíveis nos veículos Vehicular Ad-hoc NETwork (VANET)-equipados para aumentar a dinâmica do processo de selecção. O Vanet Connection Manager (VCM) é um gestor de conectividade optimizado para ambientes veiculares, que considera a disponibilidade de redes Wi-Fi, redes celulares e a tecnologia WAVE/ DSRC para veículos. Este gestor tem em conta a velocidade e direcção do veículo, a posição das infraestructuras bem como a sua disponibilidade, o número de saltos até ao destino, além da qualidade do sinal. O mecanismo proposto é baseado num Processo Analítico Hierárquico que combina várias redes candidatas, parâmetros geográficos e factores físicos para determinar a melhor ligação possível, incluindo a tecnologia e a melhor rede, para cada utilizador. Para o cálculo das prioridades de cada parâmetro, foi proposto o método das combinações emparelhadas desenvolvido por Saaty, optimizando o processo através de simulação e recorrendo a um Algoritmo Genético. Para observar o desempenho do gestor de conectividade, implementaram-se dois gestores típicos de conectividade: Basic Connection Manager (BCM) que apenas tem em conta a força de sinal para escolher o melhor candidato, e o Preference-based Connection Manager (PCM) que tem em conta as preferências dos utilizadores para além da força de sinal. A avaliação foi realizada num cenário Manhattan, composto por vários veículos com modelos de simulação importados do SUMO e infraestrutura aleatoriamente colocada ao longo do cenário. Os resultados mostram que o VCM apresenta melhores resultados que os outros dois gestores de rede, provando que é capaz de operar em qualquer cenário, minimizando as perdas de dados e com um reduzido número de mudanças de rede.

Keywords VANET, Handover, IEEE 802.11p, AHP, Connection Manager, Genetic Algorithm, Infrastructure

Abstract The unique characteristics of VANETs, such as high mobility, dynamic topology and frequent loss of connectivity, turn the network selection scheme into a complex problem. In a crowded wireless environment that surrounds us, mainly in urban areas, there is a proliferation and superposition of multiple networks and technologies. Therefore, in order to guarantee connectivity in a transparent way for users, the presence of a connection manager capable of taking informed decisions is crutial. With the increase of mobile traffic, several initiatives have been performed for deploying free/low-cost Wi-Fi hotspots across the cities, in order to offload traffic from the cellular networks into more cost-effective networks. On the one hand, clients benefit from lower data prices, and on the other hand, operators may reduce the amount of cellular infrastructure deployed. Furthermore, users will certainly prefer to connect to a free source of Internet whenever it is available instead of paying for it. Since nodes in VANETs are vehicles, the perception of the surrounding networks is constantly changing, becoming unstable with speed. Therefore, the high mobility of nodes in VANETs jeopardizes the existing network selection mechanisms, which for the network election, are based on Received Signal Strength (RSS) to choose where to connect. Moreover, in a VANET environment, there are no mechanisms capable of taking into account V2V communication according to the WAVE/DSRC technology. Thereby, we propose a connection manager which considers the Wi-Fi networks, cellular networks and the WAVE/DSRC technology to provide connectivity to vehicles. This connection manager is capable of looking into relevant data that is available in VANET-equipped vehicles, increasing the dynamic of the decision process. VCM is a connection manager optimized to operate in VANET scenarios, which takes into account the vehicle speed and heading, the infrastructure position along with their availability and also the number of hops to reach the service provider, besides the link quality. The proposed connection manager is based on an Analytical Hierarchic Process (AHP) that combines several candidate networks, geographic inputs and physical factors to determine the best connection at all times, including the technology and the best network, for each user. To determine the priority of each parameter, we proposed the combination of pairwise comparisons between the criteria involved, according to Saaty's pairwise comparison scale, enhancing the process through simulation and using a Genetic Algorithm (GA). To observe the enhancements provided by VCM, two typical connection managers were implemented: BCM which only looks to the signal quality to choose where to connect, and PCM which takes into account users preference besides the RSS. The evaluation was performed in a Manhattan grid, composed by several vehicles using SUMO's car-following model and with equal turn probabilities, and infrastructure randomly spread across the scenario. The results show that VCM outperforms the other two connection managers, proving that it is capable of operating in general scenarios minimizing the packet loss and with a reduced number of performed handovers.

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Acronyms

AHP Analytical Hierarchic Process

AP Access Point

AU Application Unit

AARF Adaptive Auto Rate Fallback

ARF Auto Rate Fallback

BCM Basic Connection Manager

BER Bit Error Rate

BSS Basic Service Set

C2C-CC Car-to-Car Communication Consortium

CAN Controller Area Network

CCA Clear Channel Assessment

CCH Control Channel

CTS Clear To Send

DCF Distributed Coordination Function

DHCP Dynamic Host Configuration Protocol

DSRC (Dedicated Short-Range Communications

DRIVE-IN Distributed Routing and Infotainment VEhicular Inter-Networking

DOT Department of Transportation

EWM Emergency Warning Messages

FCC Federal Communication Commission

FL Fuzzy-Logic

FSM Finite State Machine

GA Genetic Algorithm

GUI Graphical User Interface

GPS Global System Position

IBSS Independent Basic Service Set

IHVS Intelligent Vehicle Highway Systems

IP Internet Protocol

ISP Internet Service Provider

ITSA Intelligent Transportation Society of America

ITS Intelligent Transportation Systems

LOS Line-of-Sight

MAC Medium Access Control

MADM Multiple Attribute Decision Making

MANET Mobile Ad-hoc Network

MGW Mobile Gateway

MN Mobile Node

MLME MAC subLayer Management Entity

M2M Machine-to-Machine

NITSA National intelligent Transportation System Architecture

NLOS Non-Line-of-Sight

OBU On-board Unit

OEM Original Equipment Manufacture

PHY Physical

PCM Preference-based Connection Manager

QoE Quality-of-Experience

QoS Quality-of-Service

RBAR Receiver-Based Auto Rate

RSU Road Side Unit

RSS Received Signal Strength

RSSI Received Signal Strength Indicator

RTS Request To Send

SCH Service Channel

SNR Signal to Noise Ratio

SSID Service Set Identifier

STA Station

TDMA Time Division Multiple Access

UDP User Data Protocol

VAC Vehicular Address Configuration

VANET Vehicular Ad-hoc NETwork

VCM Vanet Connection Manager

V2I Vehicle-to-Infrastructure

V2V Vehicle-to-Vehicle

WAVE Wireless Access in Vehicular Environments

WSM WAVE Short Messages

WBSS WAVE-mode Basic Service Set

Wi-Fi IEEE 802.11 a/g/n

WLAN Wireless Local Area Network

WSA WAVE Service Announcement

ZOR Zone of Relevance

Chapter 1

Introduction

This document was developed in the scope of the final discipline Dissertation of the Master in Electronic and Telecommunications Engineering in the Department of Electronic, Telecommunications and Informatic of the University of Aveiro, with the theme "Mobility of Communications between Vehicles and Infrastructure".

With the work performed in this Dissertation, it is expected to improve the network connection management scheme for VANETs.

In this first chapter, it is presented the motivation of the performed work, the proposed objectives, the contributions and also a brief description related to the document organization.

1.1 Motivation

The wireless networks are suffering a huge evolution in the past few years, being more and more required for communications (according to Cisco's data [1], mobile data traffic grew 70 per cent in 2012). From the other side, the vehicles world has been changing due to the suppliers, having a lot of new services incorporated in vehicles such as navigation systems (GPS), breaking sensors, board computers, velocity control systems, etc. It is expected that all classes of vehicles such as cars, buses or trucks are capable of being connected on the same network, sharing all kinds of information among them, such as alarm messages in case of accident or simply traffic congestion messages.

The necessity of providing communication between the vehicles leads to the creation of VANETs. VANETs aim to provide V2V and Vehicle-to-Infrastructure (V2I) communication with the main purpose of creating safer roads, reducing the number of accidents and consequently the number of victims. Beyond the security feature, the purpose of providing more comfortable travels to the users, improving the driving experience, and the Internet access to passengers is also a role for VANETs.

Communication in VANET is performed on DSRC in the 5.9 GHz band, that has been specially allocated by the Intelligent Transportation Systems (ITS) [2]. This kind of network has very tight requirements in terms of delay due to the need of transmitting safety information in a short period of time. However, the communication environment is in constant change due to the high mobility and interferences which lead to several challenges.

VANET communications open an unlimited number of new applications, such as location-based information dissemination for vehicular safety, vehicle-based social networking and interactive games. This way, the VANETs rise with full potential and they are getting a lot of attention from the governmental authorities, the scientific community and also from the automobile industry.

It is expected that, in the future, vehicles will be able to establish communications not only with other vehicles but also with infrastructure points strategically placed across the cities in order to provide connectivity. This infrastructure may be based on different technologies: IEEE 802.11p Road Side Units (RSUs), Wi-Fi hotspots, such as the one available in the cities (PT Wi-Fi, ZON@FON), and cellular network to provide connectivity (V2I communication). Vehicles will be able to communicate directly to the infrastructure or communicate between them through mesh networks (V2V communication), extending thereby the connectivity provided by the infrastructure units. Figure 1.1 shows several possible communication types in vehicular networks: V2V, V2I and communication between infrastructure. In this environment, it is important to choose the best network available for each vehicle dynamically, according to its needs and to the network conditions. Important factors to take into account are the following: the vehicles movement, the quality of the link, the expected contact time, the number of hops to connect to the infrastructure and the associated cost.

A connection manager that is able to make an informed and efficient decision of the network and technology to connect, in a VANET environment, is the purpose of this Dissertation.

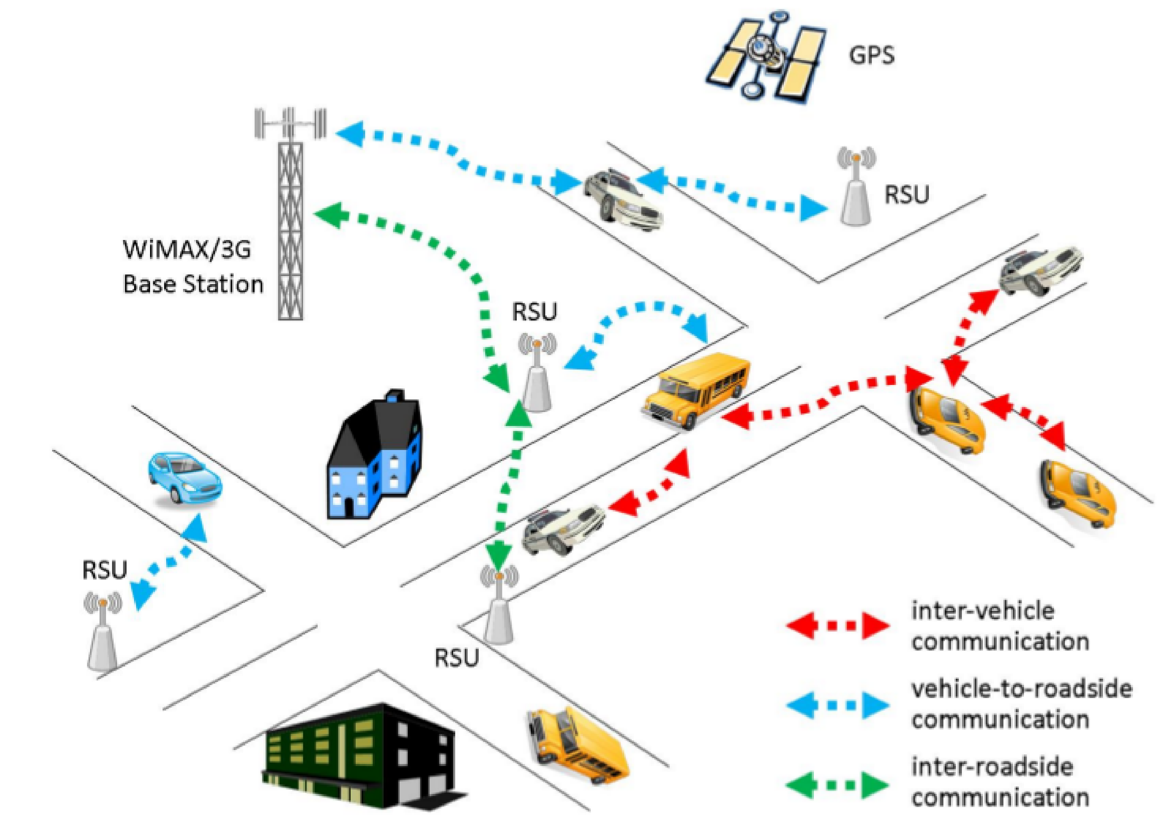


Figure 1.1: Communication schemes in VANETs, from [3]

1.2 Objectives

With the deployment of fixed WAVE/DSRC infrastructure, the available Wi-Fi hotspots across the cities and even with the cellular network available everywhere, there is a need of choosing the best access technology and the best network to connect for the best user experience.

The unique characteristics of the VANETs such as the high mobility of nodes, frequent loss of connection and the constant variation of the access medium lead to the connection management problem where the selection of a non-optimal network can result in high costs and poor service experiences. Depending on the road network and daily traffic patterns, the vehicles mobility and the node density can be highly different. Thus, wireless connectivity between vehicles is extremely dynamic and highly correlated with the position of the vehicles and the physical characteristics of the road. Therefore, with these extreme conditions presented by the vehicles, it is mandatory to find the perfect balance between real time navigation and wireless communication in order to achieve stable and efficient traffic/information flows.

Having the vehicular network operational, it becomes essential to be able to connect it to the Internet, thus each vehicle can behave as a Wi-Fi hotspot. Since more and more the operators try to reduce the traffic of the mobile networks providing Wi-Fi hotspots across the cities which is the case of the ZON@FON and the PT Wi-Fi, it is becoming quite easy to find one of them. On the other hand, the deployment of DSRC/RSUs intends to extend the connectivity among vehicles, with no associated costs, providing a good opportunity to the users of vehicles. However, for the best user experience, it is needed a mechanism for the network selection, capable of operate in this crowded environment.

This work is focused in the mobility of the vehicles and their communications with infrastructure, with the purpose of creating a network selection mechanism that takes into account informations such as the node position, speed and heading, and also informations related to the surrounding environment to elect the best connection and the technology to use in a dynamic way.

The objectives of this Dissertation are the following:

- Evaluation and determination of the factors that can be relevant to the quality of the access to infrastructure points in vehicular environment, due to their quantity and variation of the quality signal.

- Development of a mechanism capable of taking into account the amount of information available in a VANET node, besides the quality of the link, to dynamically choose the best connection among the possible candidates, in urban environments, minimizing the number of handovers and data loss while maximizing the connection time; the connection manager must be capable of taking into account different available technologies, such as IEEE 802.11p, IEEE 802.11g and cellular network, along with mesh networks.

- Implementation in simulation environment of the proposed connection manager and specific scenarios.

- Extension to multi-hop environment, providing more functionalities and accuracy to the developed connection manager.

1.3 Contributions

The contributions of this work are:

- The definition and design of a new connection manager capable of operating in VANET scenarios - VCM.
- The implementation in simulation environment of the proposed connection manager.
- An evaluation in urban environment of the developed VCM, using the mobility model SUMO, to perform real-world scenarios, proving that VCM is capable of balancing the load of the network, by accurately determining where to connect based on geographical inputs, physical factors and the cost associated, minimizing the data loss and providing stable connections.

It is important to refer that the conceptual part of the VCM was performed in a partnership with a PhD student, André Cardote.

This Dissertation will give origin to a publication in an International Journal: VCM - A Connection Manager for VANET.

1.4 Document organization

The present Dissertation is organized in the following way:

- Chapter 1 provides the contextualization of this Dissertation being presented the motivation, the proposed objectives, contributions and the document organization.
- Chapter 2 provides an overview of the main concepts of VANETs, namely historical facts, VANET architectures, specific characteristics, the main standards and possible applications, so that way the reader can easily understand the main concepts explored in VANETs. In the final part of this chapter it is presented the related work in the areas tackled in this Dissertation, such as connection management, VANET infrastructure and VANET simulation.
- Chapter 3 presents the proposed connection manager - Vanet Connection Manager, based on an AHP for the network selection problem in VANETs and using a GA for the process optimization.
- Chapter 4 presents all the developed implementation with the purpose of building the proposed network selection mechanism in simulation environment.
- Chapter 5 presents the proposed scenarios followed by their validation. The work of this chapter consists in the simulation through a Manhattan grid scenario, with random traffic, to perform the global evaluation of the VCM, while compared to traditional connection managers, also implemented.
- Chapter 6 contains the conclusions related to all developed work in this Dissertation and also the improvements that are possible to perform, as future work, providing more suitable information to the developed network selection mechanism.

Chapter 2

State of the art

2.1 Introduction

This chapter presents an overview of vehicular networks based on the literature, with the main purpose of framing the reader in this theme.

Section 2.2 contains a summary of the history of VANET, followed by the explanation of its concept in Section 2.3. Sections 2.4 and 2.5 present the unique characteristics of VANETs also with the technical challenges experienced for VANET deployment.

Section 2.6 shows the potential architectures and possible deployment scenarios, while Section 2.7 explains important concepts related to dissemination of data between vehicles, and the potential of including infrastructure in the networks.

Section 2.8 covers the IEEE standards for vehicular communications, while Section 2.9 provides some information related to addressing.

Section 2.10 explains some basic important concepts for understanding VANET applications, also with some examples.

Finally, Section 2.11 provides information about the related work, with special emphasis in connection management, VANET infrastructure and simulation.

2.2 History

In 1991, with the creation of the Intelligent Vehicle Highway Systems (IHVS) program under the responsibility of the Department of Transportation (DOT), the vehicular connectivity started to be a subject of study with the purpose of reducing congestion and the increasing road safety. The DOT, in a partnership with Intelligent Transportation Society of America (ITSA), by 1996, developed a framework for the definition, planning and integration of the National intelligent Transportation System Architecture (NITSA). However, a small spectrum band near 900 MHz, initially given for vehicular applications, was insufficient for most applications, and by the time of 1999, it emerged one system of dedicated communication in north america, the DSRC [2] with 75 MHz of band spectrum (in the 5.9 GHz) that was approved by the Federal Communication Commission (FCC) specially reserved for vehicular communications.

In 2002 the ITSA proposed the adoption of a single standard for the MAC and Physical (PHY) layers, and by the time of 2004, the IEEE 802.11p [4] development group was created. To work on the others layers, another task force was created to develop the IEEE 1609.x standards [5]. Meanwhile in Europe, the Car-to-Car Communication Consortium (C2C-CC) [6] has been initiated by automotive Original Equipment Manufactures (OEMs) and car manufacturers.

In 2010 the IEEE 802.11p became a final standard, giving origin to several projects related to VANETs.

2.3 Definition

Vehicular networks, also known as VANETs, are a new class of wireless networks that have emerged in the last years in the automotive industry due to, on the one hand, the evolution and massification of the Wireless Local Area Networks (WLANs) and the mobile networks, and on the other hand, the technology evolution that the automotive industry suffered. These networks are formed between moving vehicles equipped with wireless interfaces that can allow the communication with different access network technologies.

VANETs allow communications between nearby vehicles, V2V communication, but also between vehicles and fixed equipment placed on roads called RSUs (V2I communication). Vehicles have to be equipped with On-board Units (OBUs), considered mobile nodes, which are responsible for sending and receiving information on the network. On the other hand, the RSUs are considered static nodes, being responsible for the access to foreign networks, allowing the connection of the OBUs to them and also to the Internet. The vehicles can be of any nature: private, public transports (taxis and buses), public service (police cars and ambulances). The fixed equipment circulating on roads, the RSUs may belong to the state or simply to private network operators.

2.4 Specific Characteristics

In VANETs the nodes organize themselves without the need of a central authority: they behave as Mobile Nodes (MNs) or even as routers to another MN, like it happens in Mobile Ad-hoc Networks (MANETs). The main difference is that in VANETs, the MNs are vehicles, which leads to special behaviors, features and unique characteristics in comparison to other communications networks [7], such as the following:

- **Unlimited transmission power and higher computational capability** - Taking into account that on the vehicular networks, nodes are vehicles in opposite to classical Ad-hoc networks, they have the capacity to supply continuous power to computing and communication itself.

- **Predictable mobility** - Unlike the classic Ad-hoc networks, where it is almost impossible to predict the mobility of the nodes, in VANETs the movements of the nodes are limited to the roads. Nowadays it is possible to access to that information with position systems like Global System Position (GPS), so that, having in consideration the average speed, current speed and also the direction, it is possible to predict the trajectory of the vehicle, specially in highway scenarios.

- **Geographical communication** - In contrast with other types of networks that use only traditional communication (Unicast or Multicast), on vehicular networks it is possible to forward packets to a specific zone, according to a geographical address.

2.5 Challenges

The main characteristics presented by VANETs, such as the high mobility of the nodes and their speed, leads to several challenging characteristics [8]:

- **Potentially large scale** - In contrast to typical Ad-hoc networks that have a limited size, the potential of VANETs leads to an extension over the entire world.
- **Network fragmentation** - The dynamic nature of traffic can result in several inter-vehicle gaps in sparsely populated scenarios. Even though the coverage area supplied by infrastructure units is large, it is highly probable that it will not be enough to guarantee a fully connected network without any losses. Cellular network is always a possibility to fill possible gaps in the connectivity, however, it can bring extra costs to the user.
- **Synchronization** - In VANET communication all nodes must be able to listen periodically to a Control Channel (CCH), which means that all nodes of the network have to be exactly synchronized to access the channel on the same time slot. An easy way to accomplish that is to use a GPS in every node of the network but, it may fail if the vehicles travel into a zone where there is no satellite coverage.
- **Extreme environments** - VANETs encompass different environments with extremely different characteristics, such as the highway and city environments. In the case of highways, it is expected to have vehicles moving with speeds higher than 120 Km/h, while in terms of vehicular density it is expected to be small, around 1 vehicle per Km. On the other hand, in city environments it is expected that the vehicles move with low speeds (50 Km/h), but in terms of vehicular density it is expected to have a large density. This way, the VANETs must be ready to deal with all possible conditions of traffic, for all kinds of scenarios.
- **High mobility** - In urban areas it is quite difficult to predict the route of each node taking into account the large number of intersections, but also that there are different paths to reach the same place. The high speed of the vehicles can lead to a reduced amount of time for them to be in range of each other for communication.
- **Latency restrictions** - There are types of messages that cannot tolerate any kind of delays, mainly the safety messages. In these messages, the time for exchanging packets is minimal, where an unpredictable delay may lead to a traffic accident.
- **Network topology and connectivity** - Since vehicles are moving and constantly changing their position, the possible scenarios are unlimited and they will dynamically change, leading to different network topologies at each time. The connectivity of nodes will depend on the range of wireless links, and also on the number of vehicles on the road equipped with IEEE 802.11p.

2.6 Architectures

The VANET architectures has been a theme in constant discussion. According to Lee et. al [9], three possibilities appear to the vehicular networks as shown in Figure 2.1.

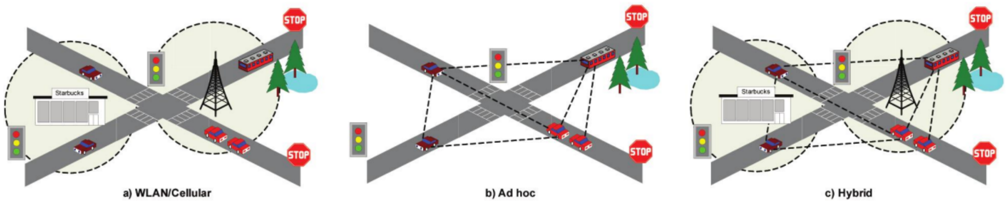


Figure 2.1: Vehicular Ad-hoc Network architectures in [9]

- **WLAN/Cellular**

  This type of architecture uses infrastructure units (RSUs) connected between them with a wired backbone, placed along the road with the purpose of guaranteeing V2I communication. These nodes centralize all the network traffic.

  The main advantage of this architecture is that it guarantees full connectivity to the vehicles in the coverage area of infrastructure units. These infrastructure units can be connected to external networks such as the Internet. The main inconvenient of this architecture is the high cost associated to the infrastructure.

- **Ad-hoc**

  This type of architecture is purely Ad-hoc, which means that it does not use any kind of infrastructure to communicate. Vehicles themselves behave as routers and forward information among them using multiple hops.

  The main advantage of this architecture is the low cost of implementation, since no infrastructure is used to communicate. The vehicles are equipped with OBUs, which guarantee the communication among them.

  The largest inconvenient of this architecture is the dependency created on the vehicular density to guarantee the communication, since there is no infrastructure to support it. Another fact is that without infrastructure, it is impossible for vehicles to access external networks.

- **Hybrid**

  This type of architecture offers as a solution one mixture of both architectures previously presented, which means that the full communication is not supplied only by the infrastructure, but merely a part. This way there will be RSUs strategically placed, enabling the maximization of connectivity of the network, being the vehicles themselves responsible for forwarding information to areas that are not covered by RSUs. Thus, it is possible to maintain the coverage area, reducing the cost of implementation (due to the fact that there are fewer infrastructure units involved).

The C2C-CC [10] proposed the reference architecture which can be divided into three different domains: Ad-hoc domain, in-vehicle domain and Wi-Fi (infrastructure) domain, as shown in Figure 2.2.

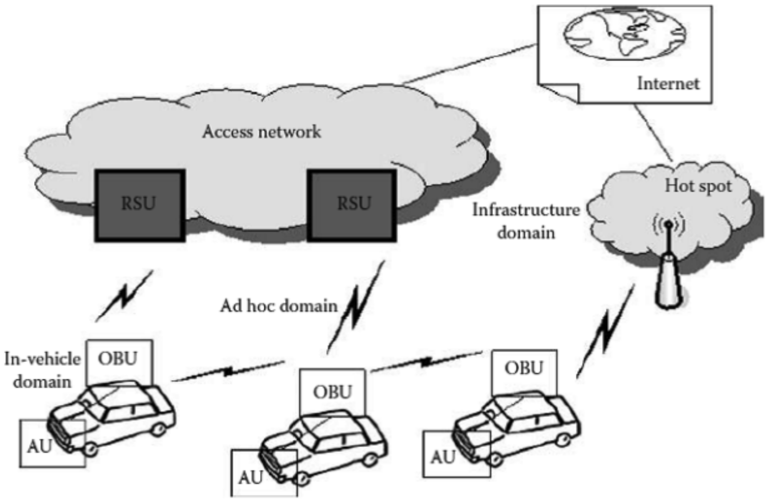


Figure 2.2: Car-to-Car Communication Consortium architecture in [11]

- **In-vehicle domain**

  The in-vehicle domain is essentially a local network inside each vehicle, and is composed by two different units: OBUs and Application Units (AUs). An OBU, shown in Figure 2.3, is considered the core of a VANET. These units are installed in each vehicle and connected to the Controller Area Network (CAN) bus in order to collect data. It has communication capabilities (wired and/or wireless). An AU is a device responsible to manage and execute a set of applications required by the vehicle, while it makes use of the OBU communication capabilities.

- **Ad-hoc domain**

  The Ad-hoc domain is a network composed of vehicles equipped with OBUs and fixed RSUs deployed along the road where both of them can be treated as nodes, in case of the RSU static nodes, and in case of the group composed by vehicle plus OBU mobile nodes.

  An RSU can be bound to a wired network, providing Internet access; their main purpose is to forward data into the Ad-hoc domain, improving the network connectivity.

- **Wi-Fi domain**

  The Wi-Fi domain can be divided into two different groups. On the one hand, the RSUs that allow vehicles to increase their connectivity and supply Internet access, and on the other hand, the Wi-Fi hotspots which exist in the area, allowing the OBUs to be installed in the vehicles to access the Internet.

  In the extreme case where are no RSUs or Wi-Fi hotspots in the area, the vehicle can always connect to the Internet using cellular network (GSM,GPRS,UMTS, Wimax LTE).

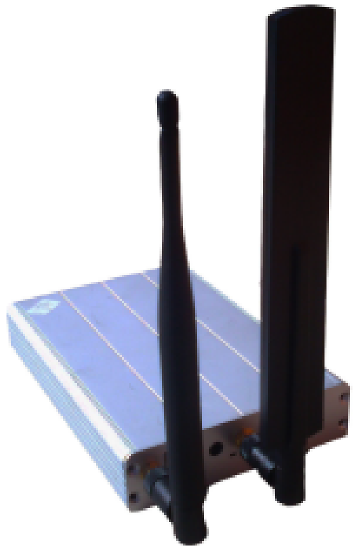


Figure 2.3: On-Board Unit

2.7 Dissemination of information

The unique characteristics presented by VANETs, such as dynamic topology of the network and the high mobility of the nodes, leads to several issues in terms of data dissemination.

VANETs must be ready to operate in extreme environments, such as urban scenarios with high density of nodes, and rural zones with low vehicular density. Thus, it is mandatory to develop capable algorithms for data transmission to guarantee the correct delivery of information.

First of all, data dissemination can be made according to the number of hops: single-hop and multi-hop which is shown in Figure 2.4.

Data dissemination using single-hop is implemented using broadcast at the MAC layer, where vehicle A sends the information to any vehicle at its range, but it cannot reach vehicle B being incapable of receiving the information. If there are RSUs at the range of the vehicle, single-hop can be performed as well, improving the connectivity and the control of the communication.

The data dissemination through multi-hop scheme requires intermediate vehicles to act as relays between the sender and the receiver; however, in order to use a multi-hop system it is required a mechanism for network routing. For example, data can be disseminated through several hops until it reaches an RSU, and then the infrastructure forwards the information using single-hop to the vehicles at range.

Single-hop and multi-hop are both needed for vehicular communications and complement each other.

Taking into account the number of destinations, data dissemination can be made in unicast, multicast or broadcast.

The majority of messages disseminated in unicast are relative to entertainment applications (games, video transmission, Internet access). When the messages have as destination

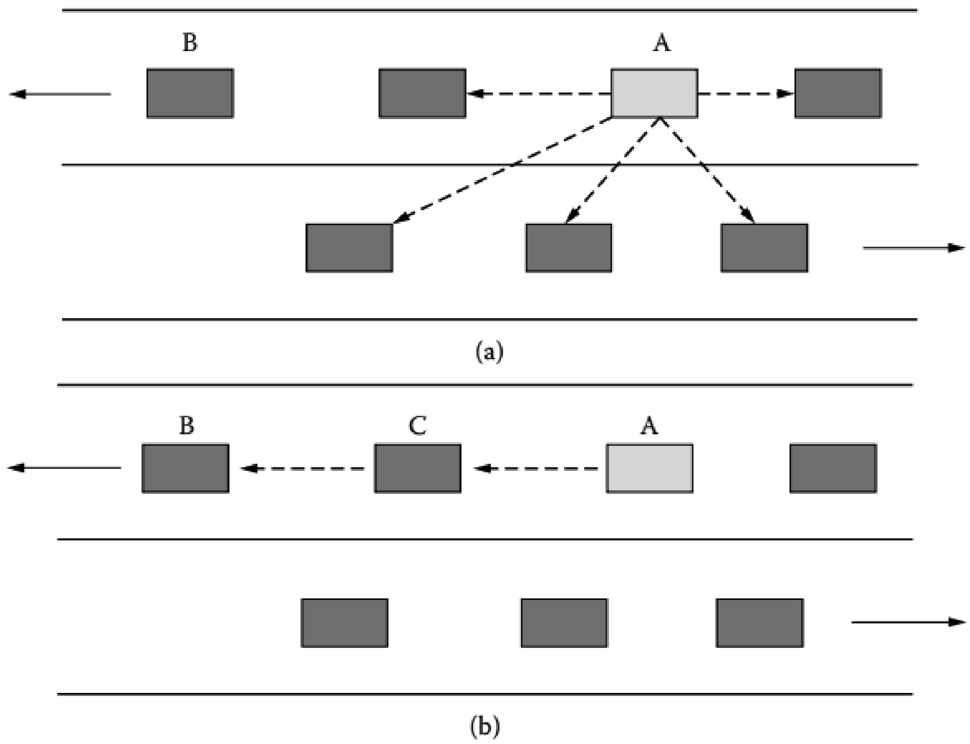


Figure 2.4: Single-hop (a) and Multi-hop (b) Data dissemination, from [11]

a specific group of vehicles, the data dissemination is called multicast. These messages are normally used to transmit information to a specific zone of the road involving several vehicles at the same time, for example one way of the road.

Finally, the broadcast transmission is when the message is addressing all vehicles at range, for example the safety messages. However, there are some safety messages that could be needed in a specific zone. Therefore, Kremer [12] creates the concept of Zone of Relevance (ZOR) which basically consists in the attribution of a certain zone where the message is important to be delivered, and only the vehicles in that area will receive it.

In a scenario where the VANETs are in a state of saturation, Moreno et al. [13] concluded that the probability in the reception of the messages disseminated in broadcast are about 20 % for 100m distances and even smaller for longer distances. The authors of [13] propose a scheme of priorities to increase the probability of successful delivery messages. On the other hand, Ni et al. [14] identified one problem in data dissemination in Ad-hoc networks, the broadcast storm which consists in the overlap of multiple radio signals at the same area due to the broadcast dissemination leading to possible collisions. Therefore, the authors proposed a dissemination scheme based on geographical inputs of the nodes.

Another scheme that tries to avoid the broadcast storm is presented by Horlait et al. [15] where the authors propose the retransmition of the broadcast messages based in a certain propability dynamically calculated based on the vehicles density around the area.

Kitani et al. [16] proposed a scheme of data dissemination to scenarios where there is not always connectivity among the nodes which is called "ferrying technique". In this scheme the vehicles are divided into 2 categories: regular nodes and message ferries. The regular nodes are the ones who move freely, while the messages ferries are the ones who have static routes, such as taxis and buses, which are responsible for the forwarding of the information to the other vehicles, covering areas without connection range. This scheme of information could lead, according to the authors, to a 50% of improvement in scenarios with low density of vehicles.

2.8 WAVE standards

To face the specific characteristics of the VANETs, IEEE developed the WAVE protocol stack, composed by the standards IEEE 802.11p and the 1609.x family, as shown in Figure 2.5.

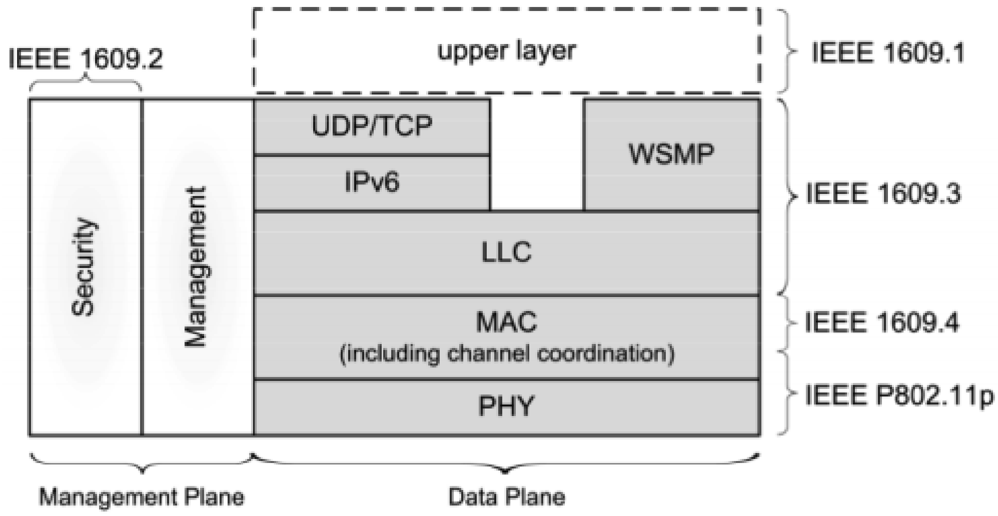


Figure 2.5: Wave stack, adapted from [17]

IEEE 802.11p focuses essentially in the lower layers: Physical Layer and Mac Layer. From the other side, the 1609.x family deals not only with Mac Layer, but also with upper layers.

2.8.1 IEEE 802.11p

The IEEE 802.11p standard was created through some adjustments on the IEEE 802.11a standard, with the purpose of defining enhancements to make the base standard more robust to face the VANETs characteristics presented previously, specially communication out of the context of a Basic Service Set (BSS), which allows nodes to avoid the time-consuming association/authentication process before exchanging information.

According to Delgrossi et al. [18], the main modifications made in PHY Layer of IEEE 802.11a, besides the frequency that changed from 5.0 GHz to 5.9 GHz, was the use of 10 MHz channels instead of the traditional 20 MHz channels providing better resilience to multipath and interference. According to Cheng et al. [19], the use of 10 MHz seems to be the best choice.

According to [20], the IEEE 802.11p standard should address important issues such as frequent disconnection, high mobility and the time-varying channel conditions, which are the inherent characteristics of VANETs.

There are two types of specified channels, CCH and Service Channel (SCH). The CCH allows a WAVE device exchange WAVE Short Messages (WSM) without the need of a pre-association, allowing the reception and the forwarding of messages in a fast approach. The SCH sends and receives IP data or WSM. The MAC layer is responsible for the channel coordination allowing that data may be transmitted in the channel Radio Frequency. The MAC layer is also responsible for the data treatment that comes from the upper layer, by changing the parameters for WAVE transmissions. The MAC subLayer Management Entity (MLME) is a management entity which uses local informations to provide synchronization functions in order to align the intervals between channels and the WAVE devices.

When one node enters an IEEE 802.11p/1609 network, it operates in CCH to acquire the configuration information. The nodes belonging to that network form one WAVE-mode Basic Service Set (WBSS), where the node that started the WBSS is called WBSS provider, and the remaining nodes are called WBSS users. The WBSS provider sends periodically WAVE Service Announcement (WSA) messages in the CCH containing several informations such as WBSS ID and the CCH number used. After receiving these messages, WBSS users can join the WBSS switching channel between CCH and the SCH used in WBSS.

In [21] Wang et al. use Network Simulator 2 (NS-2) [22] in order to study the MAC layer behavior with special focus on V2I communications. They concluded that, using the fixed size windows system present on the standard, several problems appear in terms of throughput, due to the dynamic conditions VANETs. In order to fix this problem, two different algorithms are presented (centralized and distributed) with the purpose of increasing the throughput. In the distributed algorithms, each vehicle has access to local information and calculates the backoff time depending on the channel conditions. In the centralized algorithm, it is assumed that the RSUs know the number of destination vehicles and calculate the probability of the ideal transmission. The authors concluded that both algorithms improve the IEEE 802.11p standard.

Eichler [23] showed that scenarios with high density of vehicles and with constant channel switching between SCH and CCH can result in an ineffective delivery of the safety messages. Therefore they propose an approach to reduce the number of messages with high priority to prevent long waiting queues, by giving relevance to the messages according to the benefit of the receiver node.

Bilstrup et al. [24] studied the MAC layer and concluded that, using the system of Carrier Sense Multiple Access (CSMA) in high traffic density conditions, the throughput of the communications falls around 80 percent. They also concluded that the scheme Self-Organized Time Division Multiple Access (STDMA) for real-time data traffic between vehicles brings some improvement.

Neves et al. [25] evaluated the potential of the IEEE 802.11p communications related to the range in real scenarios, concluding that with Line-of-Sight (LOS) it is possible to reach communications around 450m, and with Non-Line-of-Sight (NLOS) it can reaches around 140m.

Zhuang et al. [26] studied the impact of the mobility on the performance of the MAC layer in a scenario without RSUs, concluding that relative speed of the vehicles have a huge impact on the channel access by the MAC layer.

2.8.2 IEEE 1609.x

The IEEE 1609 family is composed by four main standards, and it is responsible for the management and control of services that the MAC layer provides. Each one is described below:

- **IEEE 1609.1** standard provides a ressource manager for WAVE which describes an application that allows the interaction of OBUs with limited computing resources and complex processes running outside the OBUs, in order to give the impression that processes are running in the OBUs.

- **IEEE 1609.2** specifies security mechanisms for applications, services and control messages and their processing.

- **IEEE 1609.3** defines the network layer of the WAVE standard, providing addressing and routing services within a WAVE system.

- **IEEE 1609.4** standard is responsible for the operations in multiple channels which define the usage time for the CCH and SCH (around 50ms for each one). It can be seen as a Time Division Multiple Access (TDMA) scheme which provides the capability of switching between the CCH and SCH very quickly with a single wireless interface. Therefore, it is possible to listen the control and emergency information periodically on CCH, independently of the load of the SCH. Hence, the GPS becomes an essential part of synchronization of nodes due to the short period imposed by the switching between the two channels (4ms).

2.9 Addressing

In VANETs the majority of the applications need some kind of addressing scheme. According to [27], the following requirements are needed for Internet Protocol (IP) addressing:

- Duplicate IP addresses are not accepted;

- The IP address must only be assigned to a node while it is in the network;

- All nodes in the network must have an IP address.

Moustafa et al. [11] propose that the same schemes of addressing that are used in MANETs could be used also in VANETs. According to [28], the addressing schemes can be divided in two types:

- **Fixed** addressing means that each node has it own fixed address assigned at the moment that it joins the network which is kept until the node leaves the network. This is the most common addressing scheme used in the Internet and for Ad-hoc networks.

- **Geographical** addressing consists in assigning one specific address to a node and it will be changing according to its movement. This address can have additional informations related to the node, such as the heading, the speed and also the type of the vehicle.

Due to the reduced connection time between VANET nodes, the time for acquiring an IP address must be very small. Therefore, Palazzi et al. [29] propose the Vehicular Address Configuration (VAC) which intends to improve the efficiency of the process through the dynamic election of one leader that acts like a Dynamic Host Configuration Protocol (DHCP) server to another vehicles, reducing the addressing time. According to the authors, with this addressing scheme it is possible to get a smaller configuration time.

Beyond this approach, the addressing scheme ”Best-Effort” is also quite common but does not guarantee the exclusiveness of each address. This approach can lead to conflicts if nodes with the same address try to communicate. According to [30, 31], the authors concluded that this approach is not the most suitable for real time applications due to the possibility of duplicate addresses. As a result, the authors propose detection mechanisms to avoid the overhead.

2.10 Applications and Services

As mentioned before, the main purpose of vehicular networks is to increase road safety. However, several other concepts can be exploited at commercial level. Therefore, it is expected that besides the safety applications, users can enjoy several other comfort applications and traffic management applications, improving the travels of the vehicles. Thus, vehicular applications can be divided in safety, traffic efficiency and comfort applications with several technologies involved, [32, 11].

The safety applications in real-time focus on the main purpose of VANETs. These are responsible to look up for the roads, vehicles approach, etc. Therefore the main purposes of these applications are to reduce the number of accidents (minimizing the human deaths on roads) providing information to the vehicle users such as warning collisions, road conditions, among others. Relative to the traffic efficiency applications these are aiming to improving the traffic efficiency on the roads as the name suggests. The expected consequences are less traffic jams, reductions of the fuel consumption and improving traffic light management, providing shorter waiting times for the vehicle users. The comfort applications have the purpose of providing to the vehicles users infotainment services as Internet access or streaming musics and videos [32, 11], making the vehicle users travels more attractive.

2.10.1 Safety applications

The main characteristic of the these applications is the critical information exchange with low-delay transmission over a Zone of Relevance (ZOR). According to Kihl [11], the safety applications can be divided into: Cooperative Collision Avoidance (CCA) and Emergency Warning Message (EWM).

2.10.1.1 Cooperative Collision Avoidance

The purpose of the CCA applications is to avoid any kind of collisions between vehicles (chain collisions frequent in highways or frontal collisions frequent in two lane roads). The CCA alerts drivers in potential collision route in order to give them enough time to take proper decisions. Biswas et al. [33] concluded that safety messages can have at most 100 ms of delay to be efficient. Thereby, the infrastructure-based solutions do not fit due to the reduced delivery time of the messages, being the V2V communications the proper solution.

Figure 2.6 represents an example of a safety application, where an accident occurred and that information was sent to the nearest RSU, which forwards to all vehicles at range.

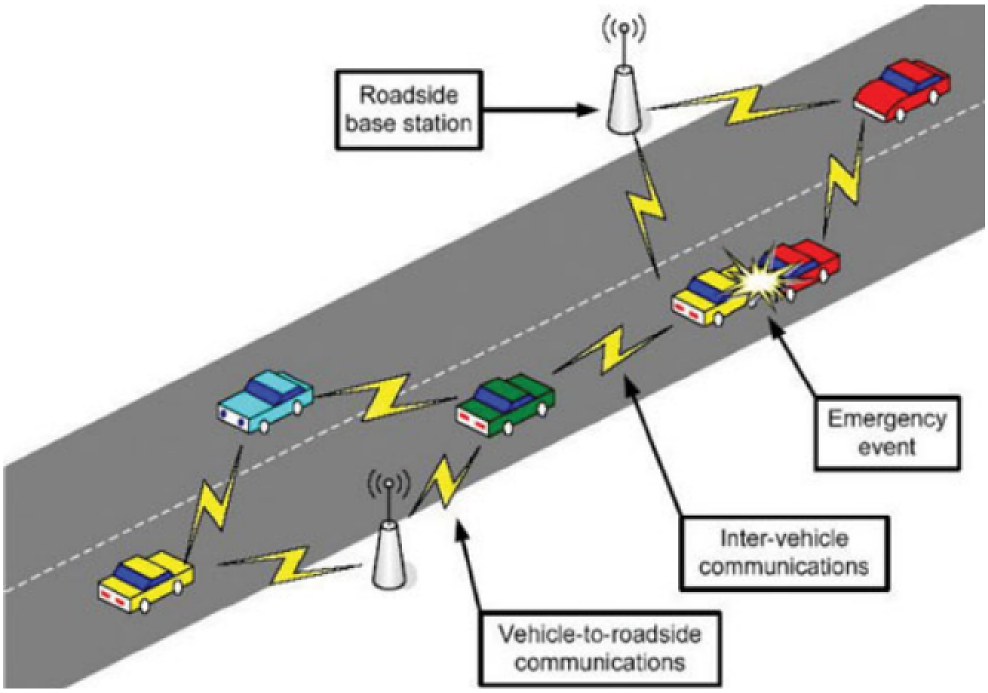


Figure 2.6: Safety application example in [11]

2.10.1.2 Emergency Warning Messages

Regarding these messages, vehicles send warnings about accidents or road conditions to other vehicles that are approaching the place. In these cases, it is important that the message remains available for a certain amount of time [32]. This kind of applications has the advantage of being easily implemented using infrastructure support because the RSUs could easily maintain the messages in the zone of relevance (ZOR). There are two categories of EWMs: instantaneous and permanent [11]:

- **Instantaneous EWM:**

  This type of messages is used to inform other vehicles about an accident or a sudden instant braking. The warning message should be addressed to all vehicles in the zone of relevance (ZOR) and it will not last for too long.

- **Permanent EWM:**

  These messages have the main purpose of warning about dangerous road conditions, therefore they will last for a long time. In this period it is needed that the messages stay in the ZOR, so when new vehicles approach the area, they can receive the message.

In EWM with permanent geocasting, initially the EWM is delivered to all vehicles in the ZOR, and then the vehicles themselves take the responsibility of detecting other vehicles entering the ZOR and warning them, as shown in Figure 2.7.

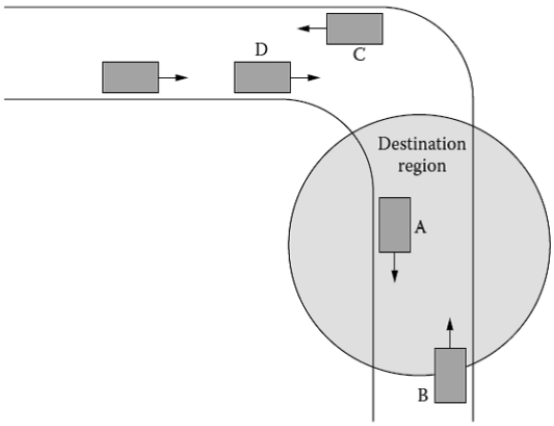


Figure 2.7: Permanent Geocasting in [11]

In order to guarantee the delivery of the permanent Emergency Warning Messagess (EWMs) in low density scenarios, [34] proposes the need of a central server responsible for the dissemination of information to the ZOR. Using cellular infrastructure, the vehicle sends the EWM to the base station responsible for that area, and it is the base station that will notify the remaining vehicles that are approaching the ZOR.

2.10.2 Traffic efficiency applications

These applications have the purpose of improving the road circulation providing faster trips and reducing not only the traffic jams but also the fuel consumption. The main difference between these applications and the safety applications referred before is that these do not have tight restrictions in terms of delay. The aim is to inform the driver about traffic conditions, therefore they are more delay tolerant.

According to [11], the traffic efficiency applications can be divided into: Traffic Monitoring and Intersection Assistance.

2.10.2.1 Traffic Monitoring

This type of applications can provide high-resolution, localized, timely traffic information for several miles around the current location of the vehicle. In these applications the roads are divided into segments where each vehicle gathers information in the segment where it is (the speed for example) and shares that information into the ZOR. According to Chang et al. [35] these informations will improve the efficiency of the mobile navigations.

2.10.2.2 Intersection Assistance

Another type of applications is related to the road intersections. These specific points are critical points in terms of accidents and traffic efficiency. One possible system is virtual semaphores in each vehicle. According to Ferreira et al. [36], this system can increase the traffic efficiency over 60 percent in high density scenarios, besides the reduction of accidents in these specific points. The inconvenient of this system is that in order to work well, all vehicles must be ready for the vehicular communications and must have the system installed.

2.10.3 Comfort applications

The main purpose of these applications is to make the vehicle journeys more interesting for the users. In these applications the vehicular network is used to supply Internet access to be used inside the vehicle. Several technologies can be incorporated to increase the connectivity such as cellular networks (UMTS,LTE), IEEE 802.11 a/b/g, WiMAX and IEEE 802.11p. These applications make it possible to provide several services to the passengers such as Video on demand, music streaming, news or simply Internet access.

Service announcements made by hotels, gas stations, restaurants and others are examples of information that vehicle users could receive when crossing the area [37, 32].

2.11 Related Work

After the general concepts of VANET have been presented, this section will focus on the related work in the area, emphazying the concepts of connection management and network selection, approaches with RSUs and VANET simulation.

2.11.1 Connection Management

Network selection has been well studied for scenarios with low mobility; however when the subject is VANETs, the scenario becomes substantially different due to the speed of nodes.

In a multiple access technology environment that surrounds us, the concept of "Always Best Connected" [38] makes total sense. This concept intends to provide users connectivity to applications using the devices and access technologies that best suit their needs. The concept of being always connected combines two related ideas, the full time connectivity and the selection of the best access technology. All this new environment brings the need of a network selection mechanism to help mobile users to select the optimal network at any given location and time.

The concept of best available connection is quite difficult to define. It carries great complexity due to the number of the variables involved in the decision process and the limited time to execute it. It is necessary to take into account several factors such as applications requirements, available network resources, coverage area, operators and Internet Service Provider (ISP) policies, and also personal needs and Quality-of-Service (QoS). The problem of the best decision becomes even harder when mobility is introduced and the possible solution is to use highly optimized selection algorithms to try to solve it.

Kosmides et al. [39] focus on the network selection problem when users are equipped with multimode terminals. The authors address the problem with the introduction of an utility-based optimization function, and developed a greedy heuristic algorithm which exploits the special characteristics of the network selection problem. Comparing the efficiency against three proposed bin-packing heuristics, it showed better performance.

In a similar approach, Rouskas et al. [40] identified several aspects of access selection and resource allocation, and formulate network selection as an optimization problem, which attempts to maximize a utility-based objective function under requirement and capacity constraints.

Ormond et al. [41] studied the need for an access network selection decision strategy which aids users operating in a heterogeneous multi-network wireless environment. The authors propose a consumer surplus based algorithm that selects the best available network for transferring non real-time data, with user specified time constraints. The proposed algorithm was compared to an always cheapest strategy, and simulation has shown better performance in transfer completion time for the consumer surplus based strategy. However, the authors referred the need of some criteria for users to make their choice and evaluate their decision looking at the consequences of each alternative.

Agoulmine et al. [42] conducted a study based on utility theory to define an appropriate decision mechanism, where they propose new single-criterion and multi-criteria utility forms to best capture the user satisfaction and sensitivity facing up to a bundle of access network characteristics.

OBrien et al. [43] proposed a scheme for the problem of handovers in an integrated radio and optical wireless system. By performing a proper vertical handover between the two media, a better QoS can be reached and low packet transfer delay. The authors propose a Fuzzy-Logic (FL) based decision-making algorithm for the vertical handover problem, which is capable of adapting the network and the traffic changes and combines the metrics to make the decision with low costs. It also prevents unnecessary handovers by classifying the communications interruptions into short and long.

In [44], the authors proposed a different approach for the network selection. They proposed a decision process that combines non-compensatory and compensatory Multiple Attribute Decision Making (MADM) algorithms, which ranks candidate networks taking into account the best service delivered to the terminal.

In [45], Shen et al. proposed a network selection scheme considering muiltiple Quality-of-Experience (QoE) criterion. The authors used an fuzzy AHP which derives relative weights from consistent fuzzy comparison matrices.

In [46], Marti et al. proposed a solution for network selection that takes into account the user preferences, network conditions, and also the service requirements. The authors proposed a network selection in cellular/Wi-Fi scenarios using both AHPs [47] and Grey Relational Analysis [48].

Niyato et al. [49] studied the dynamics of network selection with a different approach: the theory of evolutionary games in a heterogeneous wireless network. The authors proposed two algorithms for network selection: the population evolution algorithm which uses information from all users in the same service area, and the reinforcement-learning algorithm which learn the performances and prices of different networks by interaction.

In [50], Barghi et al. proposed a predictive gateway selection scheme, capable of using the vehicle movement parameters to select the route with the longest lifetime by predicting the future location of neighbors, to connect to the infrastructure. This protocol aims at spreading advertisement messages through multi-hops without considering seamless handovers and without flooding the network. Through simulation, the proposed protocol has shown better results than existing protocols, in terms of packet delivery ratio and delay, such as AODV (Ad-hoc On-Demand Distance Vector), in a highway scenario. The authors considered improving the relay selection scheme by considering more factors, such as the signal quality of the received signal, because in congested scenarios the proposed protocol may be ineffective. However, the proposed protocol was not implemented in urban scenarios and it only considers stationary gateways.

Benslimare et al. [51] proposed a heterogeneous integration of VANET and 3G networks using mobile gateways, i.e. vehicles. The authors proposed a solution for gateway selection, advertisement, and discovery for architectures that integrate 3G/UMTS networks with VANETs, which intends to minimize dead spots through this integration. In this architecture the minimum number of gateways is selected to connect vehicles to 3G network, per time instance. For the selection mechanism of vehicle gateways, route stability, mobility features, and signal strength of vehicles are taken into account. Therefore, it is expected that this architecture prevents frequent handoffs at UMTS base stations and the associated signaling overhead. By adopting this architecture, even vehicles without 3G interface can access the UMTS network. In terms of Packet Delivery Ratio and throughput, the obtained results were quite positive, while achieving reduced control packet overhead and minimized delays and packet drop rates.

Using different metrics for the gateway selection mechanism, Manoharan et al. [52] proposed an adaptive gateway management mechanism for multi-hop B3G (Beyond 3G) networks. The authors used multi-attribute decision making theory and simple additive weights techniques to select an adequate gateway based on UMTS signal strength and speed of the gateway candidates.

Setiawan et al. [53] proposed an optimal mechanism to select the appropriate gateway taking into account multiple node metrics such as the remaining energy, mobility and number of hops, for interconnected MANETs with infrastructured networks. To optimize the selection mechanism, the authors use a Multiple Criteria Decision Making (MCDM) method called Simple Additive Weighting (SAW) in order to outrank the optimal gateway node. This method was used to calculate the weights of gateway nodes taking into account those three metrics. Through simulation, the authors observed improvements in terms of throughput performance, gateway lifetime and packet delivery ratio.

In [54], Leung et al. proposed a new server and packet relay mechanism that minimizes the rate of server hand-offs by relaying location update packets towards the server that has the lowest possibility of disconnection. The authors also proposed a tuning factor which can be used for decision making based on tolerable delay and cost. Through simulation, the authors achieved lower costs and acceptable delays while compared to other methods, such as associativity-based routing, shortest path selection and quorum-based location method.

Baldessari et al. [55] proposed a solution that provides dynamic connectivity management for vehicular communications. The authors used a criteria based model to achieve the optimal path: the number of wireless hops between nodes and the geographical distance between them. The proposed solution is not suitable for our problem due to the reduced number of criteria involved in the network selection mechanism.

In [56], Zhang et al. proposed a network-controlled group handover scheme in heterogeneous vehicular networks which intends, on one hand, to maximize the system throughput and to minimize the system latency cost, and on the other hand to balance the overall load among all access networks. They formulate the handover issue as a combined cost function and propose a distributed greedy algorithm, which consists of two main steps. In the first step, an auction based method is performed to realize initial network selection, and in the second step, the users switch in a greedy fashion among the candidate attachment points in order to get the final optimal solution.

Although 3G networks can be used to support the network connectivity, Wi-Fi infrastructure has the advantage of low cost, easy deployment and high bandwidth. Therefore, a achievable alternative is provided by WLAN APs that are being installed in several countries. Even though a higher bandwidth can be achieved, it is not a satisfactory solution due to the limited transmission range. Therefore, Arnold et al. [57] proposed a relay-based solution to extend the service range of the infrastructure unit, where through simulation, it was possible to observe the improvements in terms of throughtput and AP coverage. Even though the authors considered the mobility pattern of vehicles, they do not considered the influence of speed on the stability of the proposed scheme.

Network selection for low-mobility scenarios has been presented along with several solutions proposed to implement it. However, in a high mobility scenario, studying the network selection becomes more complicated. The specific characteristics of VANET, such as high mobility, frequent loss of connection and constant change of available networks turn the network selection mechanism into a complex problem. The decision time will be very important for the performance of the system. Moreover, none of these solutions take into account the IEEE 802.11p technology along with IEEE 802.11g and cellular network, which is the focus of our problem. A selection mechanism capable to operate in VANET scenarios with all these technologies is not yet available. Another important fact is the multi-hop extension that we want to consider, providing the possibility to vehicles forming a mesh network, using the IEEE 802.11p, to connect to the infrastructure.

It is possible to take into account the information that a VANET node contains such as speed and location, that can make the decision process more accurate. We propose a new mechanism for the network selection for VANETs, capable of taking into account geographic inputs, such as the vehicle speed, heading and the infrastructure postion, preferences and physical conditions, such as the availability of the candidate and the number of hops ot reach the service provider, and to predict the best available connection.

2.11.2 VANET Infrastructure

The dynamics created by the mobility of nodes make vehicular networks vulnerable to partitioning. Moreover, the limited radio range and small penetration rates of vehicles equipped with DSRC can lead to the disconnection between nodes in a VANET, leading to sparse networks. Although a pure V2V network is possible, it may not be enough to ensure the good behaviour of the network when it is sparse. Thereby, RSUs can be deployed to overcome this problem and also to improve the network quality. This infrastructure consists of fixed base stations deployed to increase the overall coverage of the VANET.

The RSUs are expected to enhance the network connectivity improving the propagation distance of messages and serve as a backbone, providing access to the Internet. However, the cost of deploying and supporting RSUs can be extremely high. Therefore, the number of deployed RSUs must be as minimum as possible, but they must still guarantee the network connectivity.

Wischhof et al. [58] proposed the use of RSUs to connect groups of isolate vehicles. In this system, when a vehicle receives a message, it sends it to the nearest RSU which will broadcast it to all vehicles in range.

An important design consideration for any real scenario is the physical distribution of the fixed infrastructure to achieve the optimal communication and to reduce the amount of units deployed.

Kchiche et al. [59] proposed strategies for RSU deployment at popular junctions by using a central measure, and presents the ideal position for the infrastructure at places where traffic density would not lead to disconnection.

On the other hand, Reis et al. [60] studied the effect of including infrastructure points as relay nodes in sparse vehicular networks to improve communication in highway scenarios. The authors developed mathematical models to analyze the improvement brought in connectivity by RSUs in two different scenarios: *connected*, where there is a backbone link connecting all the RSUs, and *disconnected*, by measuring the *re-healing time* which is the time required to transmit information between source and destination through an RSU. They have concluded that this time is significantly reduced in the presence of RSUs.

Casetti et al. [61] proposed the deployment of fixed infrastructure units, called *disseminations points*, by focusing in the maximum number of vehicles that get in contact with them to optimize their placement. The proposed mechanism maximizes the number of delivered messages ignoring the connection stability. The authors only considered V2I communications in this work.

Cardote et al. [62] proposed a 3D urban infrastructure provisioning mechanism and mobile gateway selection mechanism for VANETs. The solution is based on Genetic Algorithms, using real-world data as input, and determining the best sites to place infrastructure.

For the developed work, we have considered different infrastuctures units according to the technology: IEEE 802.11 RSUs, IEEE 802.11g Wi-Fi hotspots and cellular network. They will be used to on the one hand, behave as a bridge between cluster of vehicles, and on the other hand, will be used as gateways to other networks. For the deployment of infrastructure units to achieve the optimal priorites, we have considered popular junctions near the roads, and increase this way the connectivity to vehicles.

2.11.3 VANET Simulation

Vehicular network simulation is essential for the development of new protocols and systems before advancing to real-world experimentation. In order to minimize the gap between simulation and reality, the simulation mechanisms must be as accurate as possible [63, 64], reducing the the number of experimentations. In this section, we will analyze two essential parts of VANET simulation: **Network Simulators** and **Mobility Models**.

2.11.3.1 Network Simulators

There are several network simulators available nowadays. According to the needs, the most suitable for VANETs simulation are described in the following paragraphs.

- QualNET [65] was developed at the University of California and is maintained by SCALABLE Network Technologies. It is a commercial version of the GloMoSim [66] and it provides accurate wireless simulation models based on Bit Error Rate (BER). Besides having a powerful Graphical User Interface (GUI), it also includes several propagation models such as CORNER[67], specially implemented for VANETs.

- NetSim [68] was developed in 2002 by Tetcos, in association with Indian Institute of Science. It is a stochastic discrete event simulator which provides network performance metrics at various abstraction levels, such as Network, Node and a detailed packet trace. Several networking technologies and protocols are available including MANET, Wi-Fi, IP, QoS, VoIP, etc. This network simulator comes with an in-built development environment, which serves as the interface between Users code and NetSims protocol libraries and simulation kernel.

- OMNet++ [69] is an extensible, modular, component-based C++ simulation library and framework, primarily built for network simulation. It offers an Eclipse-based IDE, a graphical runtime environment and extensions for real-time simulation, network emulation, database integration and several other tools.

- GNS3 [70] is an open source software that intends to simulate complex networks while being as close as possible from the way real networks perform. It provides an intuitive graphical user interface to design and configure virtual networks and it is based on Dynamips, Pemu/Qemu and Dynagen.

- NS-2 [22] is a discrete event simulator targeted for network simulation. It was initially developed by the US Defense Advanced Research Projects Agency (DARPA) through the VINT project and has been for a long time the simulator chosen for academic research. It is a open-source simulator implemented in C++ and Tool Command Language (Tcl) which supports simulation of TCP, routing and multicast protocols over wired and wireless networks. Gukhol et al. [71] proceeded with IEEE 802.11p implementation which was designed to meet the requirements set for V2I and V2V communications for VANETs. However, the accuracy of its frame-level Signal to Noise Ratio (SNR) wireless model is not the best and the complex structure presented has lead to its finish in 2010;

- NS-3 [72] is an evolution of NS-2 and is very adopted by research community these days. Contrarily to NS-2, NS-3 provides a wireless model based on BER improving the a higher level of detail. Due to the modularity presented of its own implementation, it is very easy to implement new modules in C++ or Python. A comparative study of network simulators [73] chose NS-3 as the best in terms of overall performance among several other network simulators.

As previously presented there are different network simulators, all of them with unique characteristics and behaviors. In order to have a simulation as real as possible, the choosen network simulator was NS-3.17 mainly due to these factors:

- Largely adopted by the research community;

- Well documented;

- Scalable, modular and multi-technology;

- Suitable for wireless communication, providing a wireless model based on BER, increasing the level of detail;

- The implementation of new modules is easy due to the modularity of its implementation;

- Capable of simulating large amounts of nodes;

- High execution times for large and dense scenarios;

- Attention to realism where protocol entities are designed to be closer to real computers;

- Software integration which support the incorporation of more open-source networking software and reduce the need to rewrite models for simulation;
- Easy to debug.

2.11.3.2 Mobility Models

The most specific characteristic of VANET is the mobility of nodes, as referred before. Thus, for accurate simulation of these networks, an appropriate mobility model is needed. According to [74, 75], vehicular mobility models can be classified into two categories: microscopic and macroscopic.

Microscopic models aim to give a detailed view of vehicular mobility, where the behavior of a single vehicle is modeled. Each vehicle is treated as a distinct element where the behavior of the vehicle depends of its neighboring vehicles, and also of the characteristics of the driver [76]. On the other hand, macroscopic models intend to all model aspects which influence vehicular traffic: the road topology, constraining cars movement, speed limits, number of lanes, traffic patterns delineation, etc.

Traditional MANET mobility models are not suitable for VANET simulation, which leads to the development of several mobility generation tools specially designed for VANETs. These simulators can produce mobility logs that will be used in the network simulator. There are several existing mobility simulators:

- CORSIM [77] was developed by the US Federal Highway administration and uses two different microscopic mobility models according to the environment: urban and highway.
- DIVERT [78] was designed for large-scale V2V network simulation in urban environments. It is a microscopic simulator which works with real maps, under the maintenance of University of Porto. It distinguishes between the vehicles with communication capabilities and vehicles that are just moving.
- SUMO [79] is an open source simulator, highly portable, multi-modal traffic simulation, which uses microscopic mobility models and continuous road traffic simulation designed to handle large road networks with low processing requirements. It is maintained by the Institute of Transportation Systems at German Aerospace Center, being one of the most popular mobility simulators for VANETs.
- VISSIM [80] has a GUI that allows design maps and scenarios. It uses a car-following microscopic model, and also includes a pedestrian mobility model.
- FreeSim [81] is a customizable macroscopic and microscopic free-flow traffic simulator developed at the University of Alaska. It allows multiple freeway systems to be easily represented and loaded into the simulator as a graph structure. The vehicles in FreeSim can communicate with the system, monitoring the traffic on the freeways, which makes FreeSim ideal for Intelligent Transportation System simulation.
- Paramics [82] is a fully scalable microscopic traffic generator tool designed to handle scenarios as wide-ranging as a single intersection through to a congested freeway. It is used over 80 countries including commercial consultants, transportation researchers and government agencies.

- VanetMobiSim [83] is a freely-distributed, open-source vehicular mobility generator based on the CanuMobiSim [84] architecture, and is maintained by Eurocom. It was designed for integration with telecommunication network simulators. VanetMobiSim can produce detailed vehicular movement traces employing different macro and micro mobility models and simulate different traffic conditions through fully customizable scenarios.

As previously presented, there are several mobility model simulators capable of providing realistic logs of mobility with different levels of detail. We chose SUMO mainly due to the following factors:

- Includes all applications needed to prepare and perform a traffic simulation;
- Realistic simulation in terms of vehicles model: density, speed, priorities, car following model;
- Statically assigned routes, dynamically generated routes;
- Multi-lane streets with lane changing possibility;
- Easily incorporation in NS-3;
- Fast exectution speed (up to 100 000 vehicle update/s on a 1GHz machine);
- High Portability;
- Low processoring requirements.

2.12 Summary

In this chapter we provided an overview of vehicular networks based on the literature, presenting several related ideas. We have started with a summary of the history of VANET, followed by a brief definition of the concept.

Technical challenges, such as the high mobility of VANET nodes, were discussed along with the specific characteristics of these networks while compared with MANET. We have also presented potential architectures for VANET deployment followed by an overview into data dissemination schemes.

The standards originally developed for vehicular communications were presented with special focus on IEEE 802.11p and IEEE the 1609 family, explaining all the purposes and characteristics.

A set of application were chosen and divided into three categories: Safety, traffic efficiency and comfort, showing the potential of VANET.

Finally, we have presented related work, concerning connection management, deployment of infrastructure and VANET simulation.

We have presented according to the literature, several proposals of connectivity management. However, none of these are proper, on the one hand, to operate in a VANET scenario, where mobility is the main challenge, and on the other hand, to operate in multi-technology environment, including IEEE 802.11p and multi-hop scheme.

Chapter 3

Network Selection Mechanism

3.1 Introduction

In Chapter 2 an introduction to vehicular networks was presented where several related concepts were explained. Moreover, information on proposals related to connection management were discussed. In conclusion, on the one hand, the connection management solutions that have been proposed in the literature are not efficient for high mobility scenarios, and on the other hand, none of these proposals are capable of incorporating IEEE 802.11p and also considering multi-hop communication.

Therefore, in this chapter a connection manager is proposed to operate in VANET scenarios - VCM. Our solution is a new connection manager that is based on an AHP that combines several candidate networks, which takes into account the vehicle state, such as the speed and heading, and the surrounding environment, such as the infrastructure position and availability, besides the quality of link to determine which of the visible networks is more indicated for each user.

In order to obtain the optimal parameters (priorities) for the AHP, we propose to use the combination of pairwise comparisons between the criteria involved, according to Saaty's pairwise comparison scale, along with the GA combined with the network simulator NS-3 for the process optimization.

In Section 3.2 it is described the framework related to connection management problem followed by a brief description of the proposed solution in Section 3.3. Then, a description of the AHP is performed in Section 3.4, explaining the methodology and the concept of the proposed approach.

In Section 3.5 it is presented the AHP definition and also the criteria identification for the network selection mechanism, explaning the reasons for the usage of speed for pre-selection of the priorities, since it is expected different reactions at different speeds.

In Section 3.6 it is presented the priority determination of the parameters, where all the rating tables used for building the set of alternatives are shown. The explanation related to the GA is also presented in this section.

Finally, a brief summary resumes the performed work in this chapter.

3.2 Problem Statement

The specific characteristics of VANET networks, such as high mobility, frequent loss of connectivity and the constant changing of available networks turn the network selection mechanism into a complex problem where the decision time is crucial in the performance of the system.

Due to the increased occupancy of the wireless medium, the wireless networks available for a mobile node are in constant change, becoming increasly unstable with speed. Thereby, traditional network selection mechanisms which make decisions mainly according to the signal quality of the link are negatively affected by this mobility.

The problem of network selection has been thoroughly studied for low mobility scenarios; however, the high mobility jeopardizes the existing solutions for network selection mechanisms. Moreover, there is no network selection mechanism capable of taking into account the Machine-to-Machine (M2M) communication, with IEEE 802.11p technology, neither considering mesh networks.

A possible alternative technology for vehicular communications is the Wi-Fi technology. Wi-Fi hotspots can be used as a gateway to other networks; however, vehicular communication cannot completely rely on this technology due to the time-consuming association process and the small range which is around 100m, leading that the useful communication time between one vehicle and an infrastructure unit becomes too short. The high speed of vehicles increases the dynamics of the wireless medium and consequently the motion states in which they can be classified, resulting in a changing of the network characteristics. For example, for a vehicle with low speed, Wi-Fi network could be a good option, but considering a vehicle with high speed, it is no longer a valid option for the network selection mechanism.

Another important fact that needs to be taken into account is the cost for the user, which means that, in a crowded wireless environment the user will prefer to connect to a free source of Internet whenever it is available rather than paying for it. On the other hand, with the increase of mobile traffic, several initiatives have been made with the purpose of deploying free/low-cost Wi-Fi hotspots in cities to offload traffic from the cellular networks. This creates a both side winning opportunity in which the users can benefit from lower data prices and the operators can reduce the cellular traffic, reducing this way the amount of infrastructure deployed. Taking into account the massive number of vehicles across the world, having a *connected vehicle*, will lead to an increasing of mobile data, which cellular networks cannot support. Thereby, new alternatives for data transmission are required to provide connectivity.

Finally, DSRC raises as a free communication independently of the operator, with a top range of around 1000m (with antennas placed outside de vehicles) and with a very slow latency, being suitable for safety-critical information transmission for V2V communication. With the fixed deployed RSUs, it is expected to increase the communication among the vehicles.

The ideal network selection mechanism must be capable of choosing the best connection available at all times, for each user. That means not only the choice of the proper technology given its mobility, but also, inside that technology, the best network. It must be capable of operating in the environment present in Figure 3.1, where there are available IEEE 802.11p RSUs, Wi-Fi hotspots, cellular network and purely communication among vehicles (mesh networks).

Notice that a vehicle can choose to connect to another vehicle through IEEE 802.11p, as long as one of the vehicles in the mesh has a good connection to the infrastructure through IEEE 802.11p or Wi-Fi.

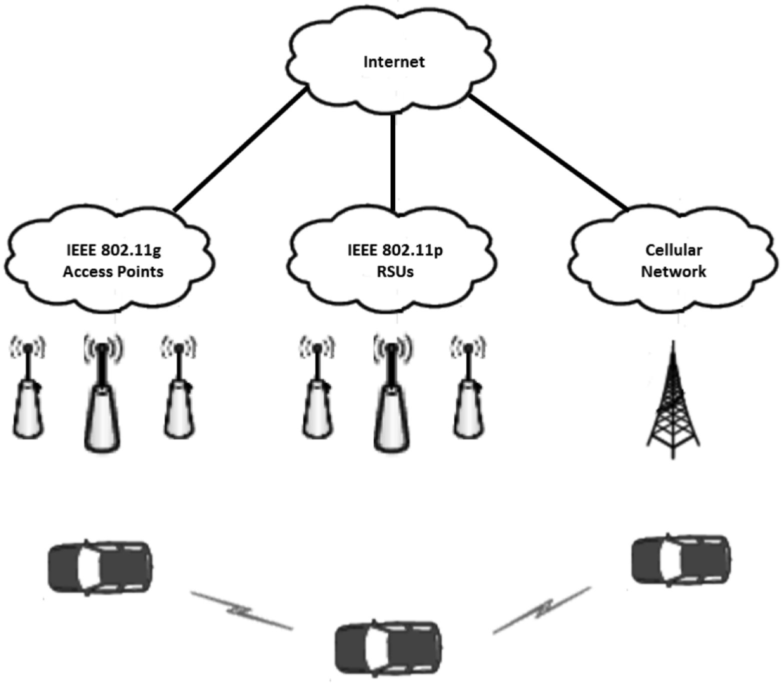


Figure 3.1: Reference Architecture

3.3 Proposed Solution

Taking into account the unique characteristics presented by VANETs and the wireless environment presented in Figure 3.1, it is concluded that on the one hand, the connection management problem should be improved by the introduction of more dynamics to the process, introducing new factors at the decision level besides the quality of the link and user preference, and on the other hand, it needs to be designed to operate in such an crowded environment, taking into account the available tecnologies along mesh networks, in order to provide a capable election mechanism to best serve the user at the lowest cost.

Therefore, we propose the design and implementation of a new connection manager to operate in VANET scenarios - Vanet Connection Manager (VCM).

The proposed solution is based on an AHP that combines several networks taking into account preferences, geographic inputs and physical conditions such as the availability, the vehicle speed and heading, and the number of hops to reach the service provider, besides the typical link quality, to determine which of the available networks and technologies are more indicated for each user.

In order to determine the priority values, we propose the combination of pairwise comparisons between the criteria involved, according to Saaty's pairwise comparison scale. Hence, we propose to use the comparison scale to rate each alternative according to its properties and enhance the process, using a GA to select the optimal values (priorities) for each of the input parameters.

3.4 Analytical Hierarchic Process

The AHP is a structured technique for organizing and analyzing complex decisions. It was developed by Thomas L. Saaty in 1971 and it has been extensively improved since then. The AHP helps people making complex decisions that involve human judgements, which can be hard to quantify.

The concept relies on the decomposition of the problem in a hierarchical manner, where the elements are sorted according to their importance for the decision. The main idea is that the participants go from the classification of general criteria into more specific aspects, creating a stratified nature of the decision. Decision making involves many criteria and subcriteria used to rank the alternatives of a decision through pairwise comparisons and relies on the judgements of experts to derive priority scales which measure intagible in relative terms.

According to [47], to make a decision in an organized way to generate priorities, for each option we need to decompose the decision into the following steps:

- Define the problem;
- Structure the decision hierarchy from the top with the goal of the decison, then the objectives from a broad perspective, through the intermediate levels (criteria and subcriteria) to the lowest level (set of alternatives);
- Construct a set of pairwise comparison matrices;
- Use the priorities obtained from the comparisons to weight the priorities in each level below.

To make comparisons, a scale of numbers that indicate how many times more important one element is over another element is needed. According to Saaty's comparison scale shown in Table 3.1, to each criterion it will be given a priority P_i.

3.5 Process Definition and Criteria Identification

After the problem has been identified and the adopted methodology has been explained, we proceed with the AHP definition, and the improvements performed such as the choice of speed for pre-selection and the hysteresis adopted to avoid unwanted variations in the network selection mechanism.

3.5.1 AHP Definition

In the previous section we made a brief description of the AHP. It is now fundamental to chose the criteria that are the most suitable for the network selection problem:

- **Price**

  The user will prefer to use the cheapest technology and network available that guarantees a minimum QoS. This criterion encompasses the following subcriteria:

  Price for the user

Table 3.1: Pairwise comparison scale, *in* [47]

Intensity of importance	Definition	Explanation
1	Equal importance of both elements	Two elements contribute equally to the property
3	Moderate importance of one element over the other	Experience and judgement slightly favor to one element over another
5	Strong importance of one element over another	Experience and judgement strongly favor to one element over another
7	Very strong importance of one element over another	An element is strongly favored and its dominance is demonstrated in practice
9	Extreme importance of one element over another	The evidence favoring one element over another is of the highest possible order of affirmation
2, 4, 6, 8	Intermediate values between two adjacent judgements	Compromise is needed between two judgements
Reciprocals	If activity i has one of the preceding numbers assigned to it when compared with activity j, then j has the reciprocal value when compared with i	

This criterion takes into account the price that the user must pay to access the network.

Price for the operator

This criterion accounts the costs related to the operator while providing access to the user, through a certain technology.

- **Received Signal Strenght (RSS)**

  This criterion is related to the quality of the link. Although it is expected that the RSS value will have lower importance in the final decision, it will still be important to distinguish the better links.

- **Backdrop** The backdrop criterion joins all the information related to the environment around the node being divided into the following subriteria:

  Resource Availability

  The resource availability is related to the availability of the candidate connections for providing connectivity to the node. This criterion is directly related to the number of nodes already connected to the possible candidate.

  Expected Contact Time

  This criterion corresponds to the amount of time that the node is expected to be in range of the possible candidate. It is an attempt of providing more stable connections, reduncing the number of unnecessary intra and inter-technology handovers.

Number of Hops to Reach the Service Provider

The number of hops influences the quality of the logical link between the node and the destination. A connection with the least number of nodes in the path will be favored in order to achieve better bandwidth.

Figure 3.2 represents the network selection problem in a hierarchic manner.

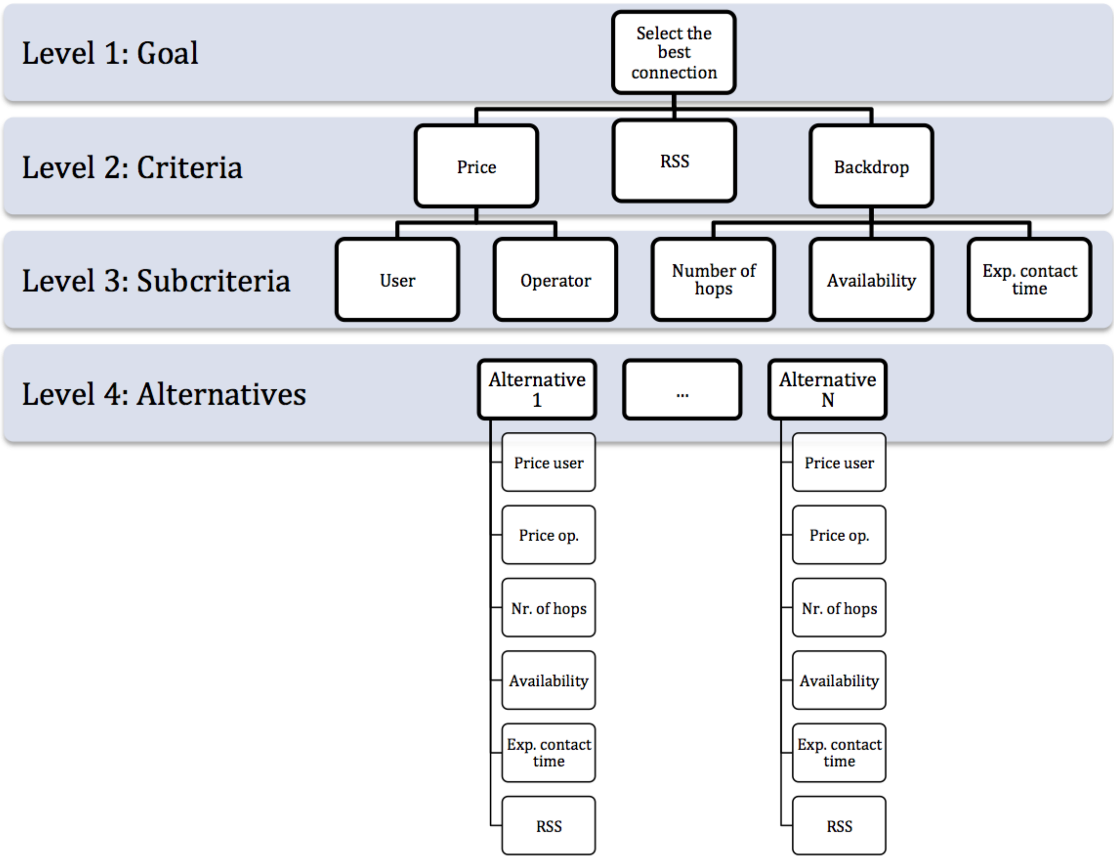


Figure 3.2: AHP representation

3.5.2 Pre-Selection

To achieve the optimal network selection in a VANET where the high mobility of nodes is the highest challenge presented, the speed will be used to pre-select the priority set for the AHP. Therefore, according to their mobility, it is proposed that VANET nodes can be classified in three categories: **stopped/very slow**, **moving slowly** and **moving fast**.

- **Stopped/Very Slow vehicles** have the lowest restrictions in terms of the number of available and convenient access technologies. They will be able to connect to free Wi-Fi hotspots at their range, but the main preference still be IEEE 802.11p since the time when they will start moving is unpredictable and may loose connectivity on the Wi-Fi link.

The cellular technology will be the last choice which means that it will be only used as a last resource due to its high latency and the cost associated.

- **Moving Slowly vehicles** can also connect to free Wi-Fi hotspots, but now with some restrictions due to the short range of the technology. The slow speed of the vehicle opens doors to prediction of the future position in the mechanism of network selection which must provide fast handovers between Wi-Fi hotspots. The highest preference for communications of these vehicles will be the IEEE 802.11p due to the higher range of the techology.

  The cellular network will be used whenever there are no other solutions available, or when it is required to provide a good QoS to fill the user requirements above all the concurrents and that fact compensates the associated price.

- **Moving Fast vehicles** can only rely on IEEE 802.11p besides cellular technology, for communications due to the high speed presented. These vehicles must quickly understand the environment and select the best network to connect at each moment.

  The cellular network is used when it is required to provide a good QoS to fill the user requirements above all the concurrents and that fact compensates the associated price.

Thus, the AHP should have different parameters according to the mobility of the nodes as shown in Table 3.2.

Table 3.2: Categories according to speed

	Speed (m/s)	**Speed (Km/h)**
Stopped/Very Slow	[0, 5[	[0, 18[
Moving Slowly	[5, 10[	[18, 36[
Moving Fast	[10, ∞]	[36, ∞]

These speed values were chosen to differenciate the vehicles according to speed, where it aims to represent real-world situations. We considered that a vehicle is in state **stopped/very slow** above 5m/s, in state **moving slowly** from 5 to 10m/s, and in state **moving fast** if its speed exceeds 10m/s.

3.5.3 Hysteresis

In the dynamic environment of the medium in which the connection manager will operate, it is expected a strong variation in some parameters such as the RSS value and the expected contact time. Thus, an extra factor was proposed, an hysteresis - H - in the network selection.

This factor must ensure that just a small variation in the priority selection will not be enough to supersede the previous network selection. Figure 3.3 exemplifies the hysteresis method.

The hysteresis value is highly dependent of the motion of the vehicle, therefore it will be generated by the GA just like the level 2 and 3 of priorities.

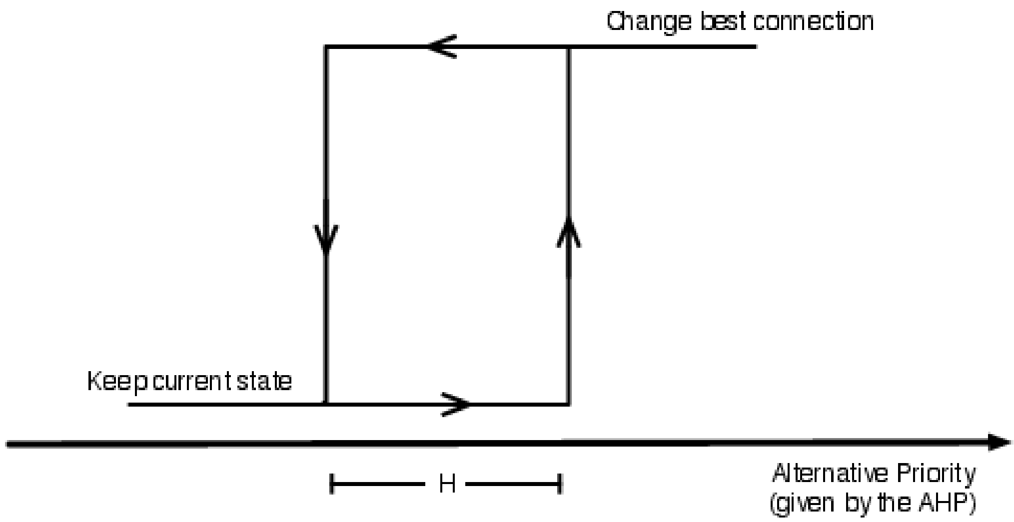


Figure 3.3: Hysteresis scheme in the election of the best alternative

3.6 Priority Determination

Now that the network selection problem has been decomposed into levels of criteria, we need to rate the available tecnology and network solutions in order to determine which is the best connection.

The priorities in the AHP are typically determined by combining pairwise comparisons between all the criteria involved according to Saaty's pairwise comparison scale. However, due to the complexity of the environment and the amount of information, in order to perform an evaluation of the alternatives, we used the GA combining with simulation. Through simulation, it has been possible to combine and experience multiple cases, importing the obtained quality metrics for each of the cases to GA.

The comparison scale has been used to rate each alternative according to its properties (level 4), and the GA combined with the NS-3 simulator have been responsible for generating the level 2 and 3 of priorities. The following sections described the way we used both approaches, comparison scale and GA, and the obtained results for level 4.

3.6.1 Comparison Scale (Level 4)

In this section, the pairwise comparison between all the criteria relative to level 4 of priorities (set of alternatives), according to Saaty's pairwise comparison scale is explained. Therefore, we predefined a set of priorities based on a quantitive scale, which represents the final rating tables for each criterion used (chosen by us according to Table 3.1) in the AHP.

p_i represents the priority of a certain criterion and the $N(p_i)$ represents the normalized priority according to Equation 3.1.

$$N(p_i) = \frac{p_i}{\sum_i p_i} \tag{3.1}$$

3.6.1.1 Price

Regarding the price criterion, we have considered the same values for both the operator and the user. However, these values can be changed, depending on the reality in study.

In Table 3.3 we show the price ratings, where it has been considered that a free connection is considered to be extremelly preferable to an expensive one (9), and moderately preferable when compared to an affordable connection (7).

Table 3.3: Price ratings for the user and operator

Price	**Free**	**Affordable**	**Expensive**	p_i	$N(p_i)$
Free	1	7	9	0.760	1
Affordable	1/7	1	7	0.192	0.252
Expensive	1/9	1/7	1	0.048	0.063

3.6.1.2 RSS

The RSS is, perhaps, the hardest parameter to grade due to its variation. Another fact that must be taken into account is the difference of RSS values presented by each technology. Therefore, we present different ratings for each technology, according to Table 3.4 for IEEE 802.11p technology, Table 3.5 for IEEE 802.11p mesh technology, and Table 3.6 for IEEE 802.11g technology.

In order to rate the RSS, we have considered a maximum RSS value for each technology, giving it the maximum rating(1). Then, we have considered that a decay of 3dBm in the signal quality causes a decreasing of the rating values. Thereby, a connection with the high signal quality is considered extremelly preferable when compared to an alternative with significally less signal quality.

It is recomended that these values be changed for each case, since we have used the noise floor to control the average range of nodes in simulation.

Table 3.4: IEEE 802.11p RSS ratings

RSS	**-66**	**-69**	**-72**	**-75**	**-78**	**-81**	**-84**	p_i	$N(p_i)$
-66	1	4	5	6	7	8	9	0.419	1
-69	1/4	1	4	5	6	7	8	0.248	0.593
-72	1/5	1/4	1	4	5	6	7	0.147	0.351
-75	1/6	1/5	1/4	1	4	5	6	0.087	0.207
-78	1/7	1/6	1/5	1/4	1	4	5	0.051	0.122
-81	1/8	1/7	1/6	1/5	1/4	1	4	0.030	0.722
-84	1/9	1/8	1/7	1/6	1/5	1/4	1	0.018	0.044

3.6.1.3 Availability

With this criterion, we propose to quantify the available resources that a certain node has to accommodate one more connection. This criterion is directly related to the upstream/downstream bandwidth, where the simplest way to perform it is to quantify the rate

Table 3.5: IEEE 802.11p mesh RSS ratings

RSS	**-39**	**-42**	**-45**	**-48**	**-51**	**-54**	**-57**	p_i	$N(p_i)$
-39	1	4	5	6	7	8	9	0.419	1
-42	1/4	1	4	5	6	7	8	0.248	0.593
-45	1/5	1/4	1	4	5	6	7	0.147	0.351
-48	1/6	1/5	1/4	1	4	5	6	0.087	0.207
-51	1/7	1/6	1/5	1/4	1	4	5	0.051	0.122
-54	1/8	1/7	1/6	1/5	1/4	1	4	0.030	0.722
-57	1/9	1/8	1/7	1/6	1/5	1/4	1	0.018	0.044

Table 3.6: IEEE 802.11g RSS ratings

RSS	**-38**	**-41**	**-44**	**-47**	**-50**	**-53**	**-56**	p_i	$N(p_i)$
-38	1	4	5	6	7	8	9	0.419	1
-41	1/4	1	4	5	6	7	8	0.248	0.593
-44	1/5	1/4	1	4	5	6	7	0.147	0.351
-47	1/6	1/5	1/4	1	4	5	6	0.087	0.207
-50	1/7	1/6	1/5	1/4	1	4	5	0.051	0.122
-53	1/8	1/7	1/6	1/5	1/4	1	4	0.030	0.722
-56	1/9	1/8	1/7	1/6	1/5	1/4	1	0.018	0.044

between the number of connected users and the maximum number of users which that node accepts. Table 3.7 displays the ratings for this criterion. We have considered that an infrastructure with at least 75 % of availability has top rating (1), and it is moderatly preferable then a infrastructure at most 50 % (2) and extremelly preferable (7,9) to infrastructures with at most 25 % and 10 % of availability.

Table 3.7: Availability ratings

Availability	**75%**	**50%**	**25%**	**10%**	p_i	$N(p_i)$
75%	1	2	5	6	0.500	1
50%	1/2	1	2	5	0.302	0.603
25%	1/5	1/3	1	6	0.150	0.300
10%	1/6	1/6	1/6	1	0.048	0.097

3.6.1.4 Expected Contact Time

The expected contact time represents in time units, for how long a node will be able to communicate with a candidate connection which the calculation is explained in the next chapter. This criterion is quite important for the network selection mechanism which intends to reduce the number of intra and inter-technology handovers, providing more stable connections and reducing the amount of processes involved. The rating of this criterion is shown in

Table 3.8. We have considered than a connection with an expected contact time with at least 25s has top rating (1), and it is moderately preferable(2) when compared to infrastructures that at least 20s of expected contact time, and extremelly preferable(5,6) when compared to infrastructures that have at least 15s of expect contact time.

Table 3.8: Expected contact time ratings

Exp. Contact Time	**25 s**	**20 s**	**15 s**	**10 s**	**5 s**	p_i	$N(p_i)$
25 s	1	2	5	6	6	0.500	1
20 s	1/2	1	2	5	5	0.302	0.603
15 s	1/5	1/3	1	6	6	0.150	0.300
10 s	1/6	1/6	1/6	1	1	0.048	0.097
5 s	1/6	1/6	1/6	1	1	0.048	0.097

3.6.1.5 Number of Hops

This criterion is expected to quantify the number of hops in a path from the source of information to the infrastructure unit. The more number of hops in the communication path, the more we aim to penalize, which is directly related to the quality of the link. The ratings for this criterion are shown in Table 3.9. We have considered that a connection with at most one hop between the vehicle and the service provider has the top rating (1), and it is moreratelly preferable when compared to a candidate with at least two hops (3), and extremelly preferable (6) when compared to a candidate with at least 3 hops to reach the service provider.

Table 3.9: Number of hops ratings

Nr. of Hops	**1**	**2**	**3**	p_i	$N(p_i)$
1	1	3	6	0.655	1
2	1/3	1	3	0.250	0.382
3	1/6	1/3	1	0.095	0.146

3.6.2 Genetic Algorithm (Level 2 and 3)

Now that we obtained the level 4 of priorities according to the Saaty's comparison scale, it is needed to explain the conceptual part for the calculation of the remaining levels of priorities through the GA.

The GA proposes several priority combinations between the parameters while refining its choise as it envolves towards convergence. Therefore, the priorities calculated by the GA are in level 2 of the AHP: *Price*, *RSS* and *Backdrop*; and in level 3: *PriceUsr*, *PriceOperator*, *Hops*, *ConnectedNodes* and *ExpContactTime*. The *hysteresis* value is also determined by the GA.

The GA generates possible solutions composed by multiple combinations of priorities and hysteresis values, and sends it to the NS-3 simulator, which returns the evaluation metrics

(D_{tx}, D_{rx}, D_{rx}^{3G} and N_h) that will be used in the fitness function defined by the Equation 3.2.

$$F = 1 - \frac{D_{tx} - D_{rx}}{D_{tx}} \cdot \alpha - \frac{D_{rx}^{3G}}{D_{tx}} \cdot \beta - N_h \cdot \gamma \tag{3.2}$$

In Equaction 3.2, D_{rx} represents the total data received, the D_{tx} the total data transmitted, D_{rx}^{3G} represents the data received by cellular networks, and N_h represents the number of handovers performed. As can be observed in the fitness fuction, we aim to penalize the possible solutions according to the data transmitted over cellular network, the number of handovers and the percentage of data loss.

The coefficients α, β and γ are weights used for each of the equation parcels, where Table 3.10 represents the used weights of the fitness function according to the vehicle motion, in order to obtain the priority values for each category of speed.

Table 3.10: Weights of the fitness function according to vehicle motion

	α	β	γ
Stopped/Very Slow	1.0	1.0	0.01
Moving Slowly	1.0	0.6	0.01
Moving Fast	1.0	0.1	0.01

The coefficient α represents the percentage of data loss, which in the case of being 100 % brings the fitness value to 0.

Coefficient β was the only one that changed through the scenatios, which is easily explained by the fact that the faster the vehicle is moving, the less it is expected to penalize the utilization of cellular technologies.

The "forced" penalization for the Wi-Fi technology is not included in the fitness function, due to the natural penalty that occurs in the association process leading to an increase in data loss, decreasing the overal fitness of the possible solution. The penalty will be observed directly in the packet loss. In the case of IEEE 802.11p, since it is a free technology, with no restrictions in terms of association process, we do not want to penalize it in the fitness function.

These priority values will be calculated in Chapter 5 in the specific scenarios.

3.7 Summary

In this chapter, the conceptual part of the proposed network selection mechanism was presented, explaining the methodology and the techniques involved.

It started by defining the problem of network selection in VANETs where on the one hand the high mobility along with the speed of nodes jeopardizes the typical network selection mechanisms, and on the other hand, none of the proposed solutions are capable of taking into account IEEE 802.11p technology and mesh networks for the selection process. Therefore, a new connection mechanism was proposed - VCM.

This connection manager is capable of operating in an environment with the coexistence of several technologies, such as IEEE 802.11p, Wi-Fi hotspots and cellular network, and it is capable of taking into account several relevant parameters that the typical connection managers do not, such as the speed of the vehicle, the position of the surrounding infrastructure and even the availability of each possible candidate.

The network connection problem was decomposed in a hierarchical manner through an AHP, which combines all the information gathered in the simulation environment and grades the possible solutions on a predefined set of priorities based on a quantitive scale. The most suitable criteria for the network selection mechanism were: **Price**, **RSS**, **Resource Availability**, **Expected Contact Time** and **Number of Hops**.

Due to the complexity of the problem, a GA was used along with the NS-3 simulator to calculate the optimized priorities for level 2 and 3.

The motion state of the vehicles was classified according to their speed into: **Stopped / Very Slow**, **Moving Slowly** and **Moving Fast**, where each of these categories will have different priority values.

In the next chapter it is presented the implementation in simulation environment of the proposed connection manager.

Chapter 4

Implementation

4.1 Introduction

After a description of the conceptual part of the proposed connection manager, the VCM, it is now important to implement in simulation environment the proposed solution.

In Section 4.2 it is presented an overall view relative to the standard IEEE 802.11 MAC and PHY at NS-3 simulator level in terms of operation and behavior, explaining the main functions and modules.

In Section 4.3 it is presented the logical network implemented to evaluate the developed network selection mechanism, where we present a description of the chosen architecture used in NS-3.

Section 4.4 presents the choises performed relative to the existing modules in NS-3 followed by the performed modifications in the network simulator classes to behave according to the requirements, such as the created functions in MAC layer, the routing method used and the implementation of callbacks to transfer parameters from different modules.

In Section 4.5 it is presented all the processed involved in the VCM, since the creation until the implementation, where it is explained the three different modules of the process: scanning module, decision module and connection module.

Section 4.6 presents two connection managers, which take into account the signal quality and users preference to determine where to connect, specially implemented to perform a comparison with the VCM, in terms of data loss and number of performed handovers.

Finally, a brief summary is presented in the end of the chapter.

4.2 802.11 MAC and PHY in NS-3

The NS-3 network simulator offers well defined models for IEEE 802.11 at PHY and MAC layers which can be divided into 4 levels:

- PHY layer models;
- MAC low level models;
- MAC high level models;
- Rate control algorithms.

4.2.1 Physical Layer

The PHY model uses a single radio interface which operates in half-duplex [85]. It has a state machine well defined:

- **IDLE** - when it is occupied;
- **CCABUSY** - when it detects the medium busy through the Clear Channel Assessment (CCA) mechanism;
- **RX** - when it is receiving a packet;
- **TX** - when it is sending a packet;
- **SWITCHING** - when it is switching channel.

Communication channel

The PHY model depends on losses and delays introduced by the communication channel modeled by the **PropagationLossModel** and **PropagationDelayModel** classes.

The channel delay in NS-3 is configured by the **PropagationDelayModel** class, which has 2 models available: *ConstantSpeedPropagationDelayModel* and *RandomPropagationDelayModel*.

The channel propagation losses are configured by the **PropagationLossModel** class in which there are 3 main available models:

- *RandomPropagationLossModel* - The propagation loss follows a random distribution;
- *FriisPropagationLossModel* - The propagation loss follows the Friis free space propagation loss model;
- *TwoRayGroundPropagationLossModel* - This model follows the Two-Ray Ground propagation loss model combining the Friis model with ground reflections;

4.2.2 Medium Access Control Layer

4.2.2.1 MAC low level layer

The low level MAC layer can be divided into 3 essential components:

- **DcfManager and DcfState** - responsible for Distributed Coordination Function (DCF) for shared medium access;
- **MacLow** - responsible for the Request To Send (RTS), Clear To Send (CTS), DATA and Acknowledge (ACK) messages;
- **DcaTxOp and EdcaTxOpN** - handles the management of the waiting queues, fragmentation, and packet retransmission.

4.2.2.2 MAC high level layer

In the high level MAC layer, it is possible to find the models for the most common wireless networks:

- **Infrastructure model-** AP which represents an access point and STA which represents a mobile node with wireless interfaces;

- **Ad-hoc model-** STA in an Independent Basic Service Set (IBSS).

Infrastructure model

This model represents a model where there are infrastructure units communicating with wireless clients, and it consists of two main classes: AP and STA.

The AP intends to represent an infrastructure unit and it centralizes the architecture, which periodically generates beacons in broadcast and accepts any attempt of association by a wireless client, STA. To join the WLAN, the AP and all wireless clients STA must be configured to use the same Service Set Identifier (SSID). The AP can be cabled to the wired network to allow STAs access to the Internet.

The STA class can have 2 behaviors, depending on the probing mode: active or passive. In case the STA is configured with active probing, it periodically sends probe requests to try to find an AP. Otherwise, in passive mode the STA waits for beacons from the AP. The STA Finite State Machine (FSM) is shown in Figure 4.1.

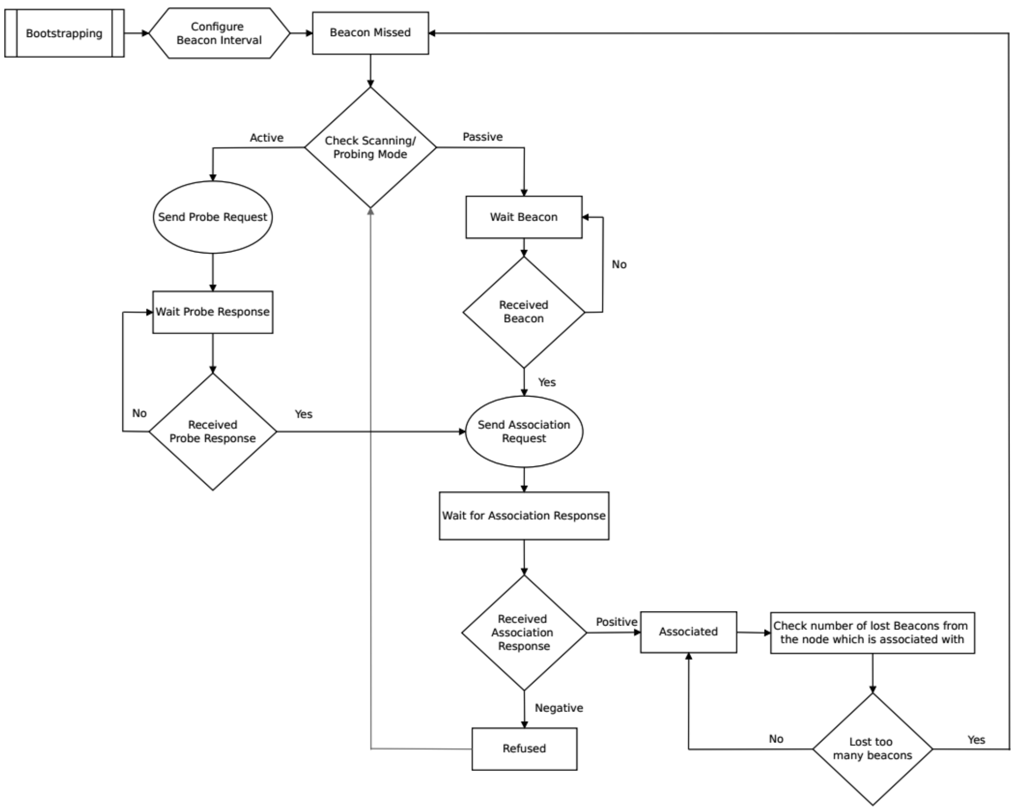


Figure 4.1: Finite-State Machine of STA class, in [86]

Ad-hoc model

In this model the architecture is decentralized, since there is no infrastructure involved. Instead, each node participates in routing by forwarding data to other nodes. These nodes are free to associate with any node in the link range. There is not a state machine due to the simplicity of the model.

4.2.2.3 MAC interrelation

When a packet is about to be sent, the device controller is notified, and the packet is set to the waiting queue. The DCF manager is responsible for the retransmission of the packet in case of transmission-failure, and also for the management of the waiting queue. When it is possible to start the transmission, the packet is sent to the MAC low level, which handles the RTS, CTS, DATA and ACK messages. Therefore, as soon as the MAC low receives the ACK, the packet is delivered to the PHY layer, which puts it in the channel transmission. The opposite process happens when a packet is received.

4.2.3 Rate Control Algorithms

NS-3 has several rate transmission control algorithms, among them:

- **ArfWifiManager** - implements the Auto Rate Fallback (ARF) algorithm [87] which uses a packet-based timer. Each sender attempts to use a higher transmission rate after a fixed number of successful transmissions, and switches back to a lower rate after 1 or 2 consecutives failures.

- **AarfWifiManager** - implements the Adaptive Auto Rate Fallback (AARF) algorithm [88]. Although this algorithm can improve performance in certain scenarios, it completely disables the ability of ARF to react to short-term channel condition changes.

- **IdealWifiManager** - implements the Receiver-Based Auto Rate (RBAR) algorithm, where all stations save the SNR of the received packets and send back these values to the transmitter, to create a transmission mode based on the value of BER.

- **CaraWifiManager** - implements the algorithm Collision-Aware Rate Adaptation algorithm [89].

4.3 Logical Architecture

With the purpose of implementing our network selection mechanism, we first need to design a logical scenario for the network that will be used to implement and test the proposed connection manager, from the physical layer to the application layer.

VCM is an application that is installed on all vehicles and will scan for available networks, decide which one is the best, and force the connection through that network.

This logical scenario which emulates a possible infrastructure deployment scheme, consists on several vehicles equipped with four wireless interfaces, one for each access technology available (IEEE 802.11g, IEEE 802.11p and Cellular) and the last one to allow communications among vehicles (IEEE 802.11p Mesh), and infrastructure deployed correspondent to each technology.

As shown in Figure 4.2, there is a server node in a separate network (10.0.1.0) which represents the Internet for example, and each technology has its own separate network. An User Data Protocol (UDP) application is installed on each vehicle, with the purpose of sending traffic to the server node at a certain rate, which will help to evaluate the performance of the connection manager.

All the infrastructure nodes are connected in a different layer 2 network, according to their technology. All the traffic belonging to a specific network is aggregated through a switch, and sent to the gateway router.

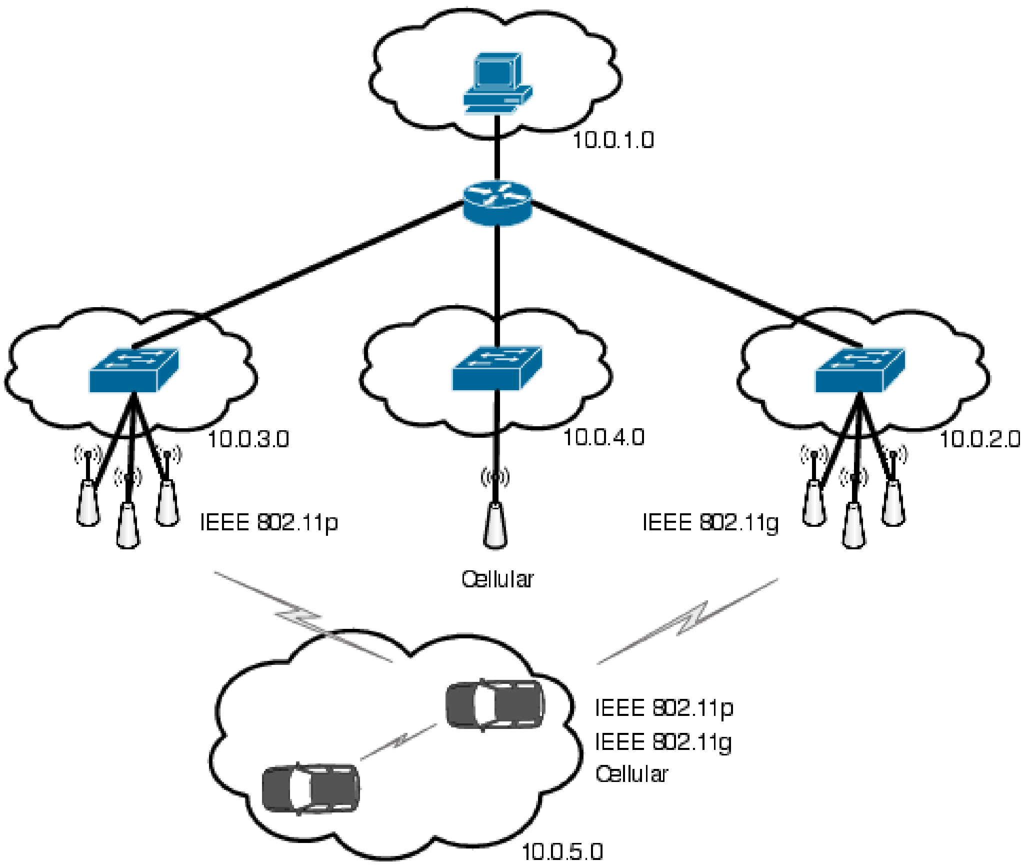


Figure 4.2: Simulation logic network implemented

Each vehicle is endowed with the capability of connecting to any of the technologies, and also forming a mesh network, using the IEEE 802.11p Mesh interface. The vehicles receive information related to the infrastructure through beacons, while they are at range. This information is processed in the connection manager, gathering all the information of the four wireless interfaces. Therefore, the VCM evaluates all candidates and according to priorities of each one, forces the connection in MAC layer through the SSID and in the IP layer through static routes, forcing the traffic of the UDP application flowing in that network.

The vehicles will move according to the mobility model imported from SUMO and will have two applications installed: a traffic application (will be the client) and VCM (responsible for the network decision).

Each technology is tuned to have the commnunication range that is shown in Table 4.1, through the noise floor parameter. The range of IEEE 802.11p is measured in our real testbed [25], and considers 450m for LOS communication and 140m for NLOS. In our simulation, we will consider 450m range for IEEE 802.11p RSUs and 140m for IEEE 802.11 OBUs (mesh).

Table 4.1: Communication ranges for each technology

	IEEE 802.11g	**IEEE 802.11p**	**IEEE 802.11p Mesh**	**Cellular**
Range (m)	100	450	140	∞

In the case of the mesh network, we considered one hop if a vehicle is connected through a RSU or an AP Wi-Fi, not performing a distinction between the IEEE 802.11g and IEEE 802.11p technology. The more vehicles are in the communication path, the more the number of hops.

According to the decision made in VCM, which will simultaneously choose the best technology and the Access Point, the traffic will flow according to that decision until it reachs the server node, which is a representation of the Internet.

4.4 Implemented Solution

Taking advantage of the existing modules provided by the simulator, the vehicles will be modulated by the STA class, while the Wi-Fi hotspots, the RSUs and the cellular network will be modulated by the AP class. Besides the offered modules by NS-3, to implement the proposed solution, several modifications were made in specific modules such as the MAC, PHY and application layer, which will be explained in the next sections.

In a first approach, we implemented the connection manager in the STA class, where it is able to receive the parameters from the infrastructure units in each wireless interface, and choose the best candidate. However, with this method it was only possible to choose the best candidate of each techology, not the best of all considering the different wireless interfaces. Due to this problem, we decided to create it on the application layer, which is installed in all vehicles, and it is capable of receiving all parameters from all vehicles interfaces and elect the best candidate from all available.

4.4.1 Communication Channel

In simulation, it is required a model to configure the losses of the medium and the delays; otherwise the environment is considered as ideal, leading to any node in scenario to receive beacons from all APs, independently of the range.

In our scenario, there will be 4 available technologies (including mesh), so in order to approach the simulation to reality as much as possible, the communication channel must be configured in terms of delays and propagation losses according to the existing models.

As previously presented in Section 4.2, in the NS-3 simulator, the PHY model depends on losses and delays introduced by the classes **PropagationLossModel** and **PropagationDelayModel**.

The model adopted for the channel delay was the *ConstantPropagationDelayModel* due to the absence of more realistic models. The *RandomPropagationDelayModel* could lead to an excess delay which could influence the simulation.

The model adopted for the channel losses was the *TwoRayGroundPropagationLossModel* which considers both the direct path, according to the Friis model, and also the ground reflection path after a certain threshold, making the simulation more realistic.

In order to define the communication range of the radio interfaces, we used the noise floor in channel configuration. With a fixed transmission power used of 16 dBm for all technologies, to limit the communication range according to Table 4.2 we used -63 dBm for Wi-Fi, -84 dBm for DSRC technology and-59 dBm for mesh network. Since cellular network has no limited range in our simulation, we did not limited the communication channel.

Table 4.2: Wi-Fi, DSRC and IEEE 802.11p mesh technologies range

	DSRC	**Wi-Fi**	**Mesh**
Range (m)	450	100	140
Frequency (GHz)	5.9	2.4	5.9

4.4.2 Rate Control Algorithms

The chosen rate control algorithm is the *ArfWifiManager* which was designed for low latency systems. It is reasonably good at handling the short-term variations of the wireless medium characteristics, in the presence of infrastructure. This rate control algorithm was also chosen due to its simplicity, and because it has no important relevance for our problem.

4.4.3 MAC Layer

In terms of the MAC high level layer models available in NS-3, the infrastructure model was adopted instead of the Ad-hoc model, due to the structure it presents, which contains the 2 main classes of our scenario, the AP and the STA class with well defined functions; however, it was needed to introduce several modifications in the referred classes to work according to our objectives.

The basic packet of information exchanged between nodes at the MAC layer is called a beacon. The AP class is responsible for the sending of beacons which contain the source and destination MAC addresses, as well as other informations involved in the communication process such as the SSID and the beacon interval. The destination is always set to all STAs, which is the broadcast MAC address. All STAs at range from the AP, configured in the same communication channel, receive and process the beacon frame.

With the purpose of including the RSS value available on the beacon frame, a modification was performed in the *MacLow* class. The NS-3 simulator provides a specific class that allows one to place a set of bytes in a packet, the *Tag Class.* Thereby, making use of this class, the value of RSS available on the *RegularWifiMac* was placed on the beacon frame.

There are two important values associated to each node (AP and STA), which were added in their creation: one for identifying the wireless interface, since the MAC layer is the same for all technology, and another to have access to the mobility model of each node, to have available the position and velocity of each node.

4.4.3.1 AP Class

The AP class performs simple functions in the MAC layer. This class centralizes all the architecture and will be responsible for constantly sending beacons in broadcast, and responding to the associations requests of the STAs at range. The range of each AP will be defined according to the technology in the communication channel previously presented.

To evaluate each GA solution, we need to account for the losses of a virtually excessive amount of connected nodes to the same infrastructue (network congestion). Thereby, to emphasize this effect, artifficially losses were created according to the Table 4.3 for IEEE 802.11g and according to Table 4.4 for IEEE 802.11p, according to the results observed in simulation.

Table 4.3: Data loss due to connected nodes for IEEE 802.11g

IEEE 802.11g	Data Loss (%)
[0,5[	0
[5,8[	25 (%)
[8,10[	50 (%)
[10,15[	75 (%)
[15,∞[	100 (%)

Table 4.4: Data loss due to connected nodes for IEEE 802.11p

IEEE 802.11p	Data Loss (%)
[0,3[	0
[3,5[	25 (%)
[5,7[	50 (%)
[7,11[	75 (%)
[11,∞[	100 (%)

One of the issues of using IEEE 802.11g for VANET is the time-consuming association process. Thereby, in order to make the simulation as real as possible, a delay of 2s was introduced in the association process for the IEEE 802.11g [90]. Concerning to the IEEE 802.11p technology, it has a time-consuming association process around 20ms [90], therefore no delay was introduced in simulation, due to the inconsiderable value of association.

In order to implement the cellular network, the adopted method was using the MAC layer of IEEE 802.11g and change the communication channel to provide unlimited range. This option was taken due to the method simplicity and taking into account that it will not interfere into our problem. Therefore, cellular network can be treated as a simple Wi-Fi hotspot with no losses, suitable bandwidth and with unlimited communication range.

The proposed mechanism as previously referred, will take into account several types of parameters, so in this model the modifications performed allow the access to the following parameters:

- The position of the AP(x,y,z);
- The current number of nodes associated and forwarding data through to the AP.

Therefore, some functions were created to perform that:

- *GetPosition*: This function is responsible for accessing the mobility model installed on the AP and returning a vector with the AP position;
- *GetAssociatedNodes*: This function returns the number of nodes that are both associated and sending data through each AP;
- *TrafficCounter*: This function is responsible for calculating the number of packets that are sent to each AP. With that information, it is possible to calculate the total traffic sent through each technology.

The returned values of the functions *GetPosition* and *GetAssociatedNodes* are placed in a tag on the beacon. Therefore, this information will be available when the STA receives the beacon.

The result of the *TrafficCounter* is used to calculate the amount of data sent through each technology, which is used in the end of the simulation in order to evaluate the VCM.

4.4.3.2 STA Class

In terms of the STA class, we used the passive probing mode, resulting in the following finite state machine presented in Figure 4.3.

There are the following possible states:

- **Wait beacon**: means that the node is not Associated and is waiting for beacons from the AP class;
- **Wait Association Response**: the STA already received a beacon from an AP and sent an Association Request to that AP, therefore it is waiting for an Association Response;
- **Refused**: the Association Response was negative, which means that the STA will not connect to that AP;
- **Associated**: the STA received a positive Association Response from the AP and it keeps the MAC Address of that AP;
- **Beacon missed**: the STA stopped receiving beacons from the associated AP (fixed number) so it disassociates, where the mobility of the STA may be the main reason.

As previously referred, the STA class will be responsible to simulate vehicles with the capability of communicating through Wi-Fi hotspots, RSUs, other vehicles and cellular network. Therefore, some modifications were performed in this class to make the simulation more realistic.

The STA class was equipped with 4 different wireless interfaces, one for each access technology (including mesh), so according to the FSM presented, it will be capable of associating on each interface to an AP configured with the same technology.

Has shown in the presented FSM, the STA is prepared to receive beacons from the AP, so it will be possible to have access to the information previously tagged in the beacon, after receiving it. Since the connection manager is an application that will be installed on each STA, it will have to process all local information. Therefore, some functions were created in this class to, on the one hand, make available some important local parameters, and on the other hand, to extract properly the information that comes along with the beacon:

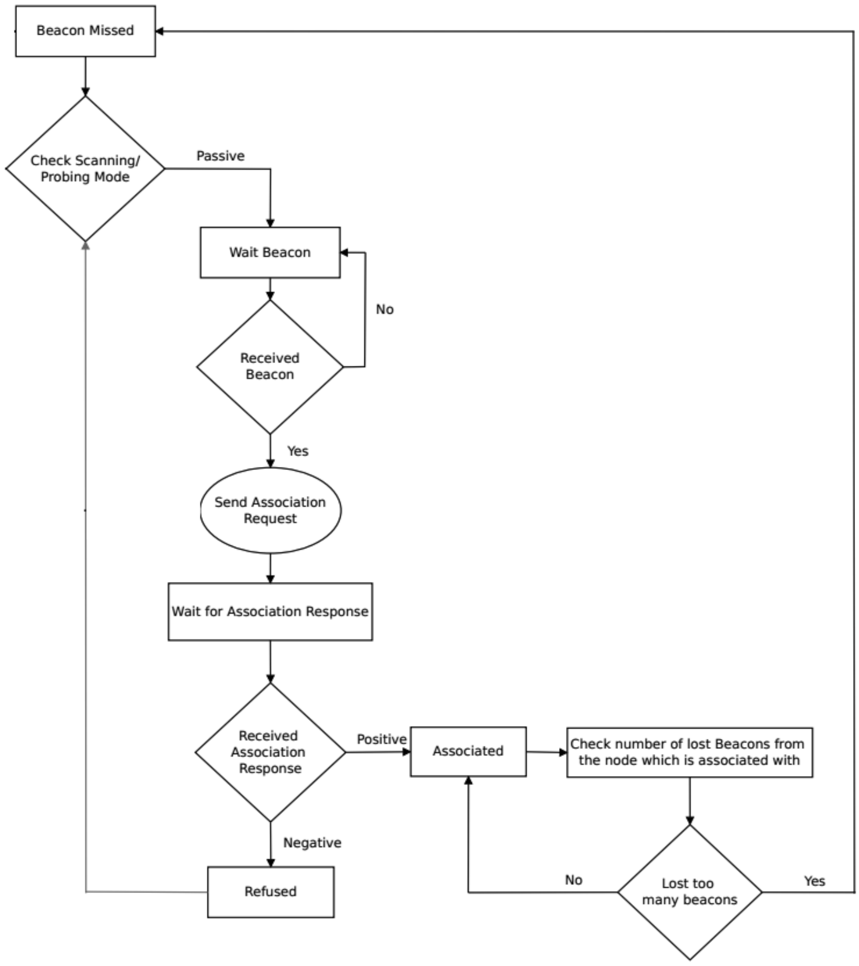


Figure 4.3: Finite State Machine adopted from [86]

- *GetPosition*: This function is responsible for accessing the mobility model installed on each STA and return a vector with the current position of the STA;
- *GetVelocity*: This function is responsible for accessing the mobility model installed on the STA and return a vector with the current velocity of the STA;
- *GetBeaconTime*: This function saves the time of the last received beacon of an AP;
- *ExtractBeacon*: This function gets the packet and extracts the tags placed there, getting the values of the position of the AP, the number of nodes connected to that AP, the RSS value of the beacon, and the respective source MAC Address.

Thereby at the receiving of one beacon, each STA will have available the following information:

- MAC Address: The MAC Address of the AP;
- Time Beacon: The time of the last received beacon of that AP;

- RSS: The RSS value associated to the received beacon;
- Position AP: The current position of the AP;
- Number Nodes: The number of the associated nodes to that AP;
- Position STA: The current position of the STA;
- Velocity STA: The current velocity of the STA.

Now that all these parameters are available on the STA class, they are ready to be processed on the connection manager. The *callback* method was used in order to transfer the parameters to the connection manager.

4.4.4 Multi-Hop Extension

With the purpose of enabling vehicles with multi-hop communication capability, the existing module *MeshWifiMac* was used as a starting point. This module simulates mesh communications where each node acts from one hand as an AP, sending beacons to the wireless medium, and on the other hand as an STA receiving beacons and having relay capabilities. This module was installed on each STA, providing one extra wireless interface. However, to work according to the reality, it is expected that only the nodes which are connected through an AP could send beacons to the wireless medium, advertising their presence. Therefore, the *callback* method was used to transfer the information from the connection manager installed on the node, to the *MeshWifiMac*, enabling the broadcast of beacons only if it is connected to an infrastructure unit.

The loss introduced by the number of hops in the communication path depends of the number of hops from the source to the Wi-Fi AP or RSU. Therefore, to evaluate each GA solution, we need to account for the losses of a virtually excessive number of hops to reach the service provider. Therefore, artifficially losses were created according to the Equation 4.1.

$$L_{hops} = 1 - 0.5^{hops} \tag{4.1}$$

In this formula, one hop more already represents a 50% loss.

Since the connection manager is an application installed on each node, it also needs to be capable of accessing and processing the information relative to this interface. Therefore, some functions were created in the *MeshWifiMac* to allow the access to information relative to the each node, and to extract that information in the receiving class.

MeshWifiMac::Send is the class in the *MeshWifiMac* module responsible for sending beacons, thereby we have implemented the following functions in this class:

- *GetIpAddress*: This function is responsible for obtaining the IP Address of the mesh interface correspondent to its node;
- *GetPosition*: This funtion is responsible for accessing the mobility model installed on the node and returning a vector with the current position of the mesh node;
- *GetVelocity*: This funtion is responsible for accessing the mobility model installed on the node and returning a vector with the current velocity of the mesh node;

- *GetHop*: This function performs a dynamic cast in order to obtain the number of hops to the access AP or RSU.

Now that the information relative to the sender mesh node is available, we need to provide functions to enable the access to the receiver mesh node. This information was placed on the beacon in *MeshWifiBeacon*, which will be available in the receiver node.

In the *MeshWifiMac::Receive*, which is the class responsible for receiving beacons acting as the STA class, several modifications were made to get access to the information related to that node, and to get access to the information relative to the node responsible for that beacon. We define the following functions in this class:

- *GetPosition*: This funtion is responsible for accessing the mobility model installed on each node and return a vector with the current position of the mesh node;

- *GetVelocity*: This funtion is responsible for accessing the mobility model installed on each node and return a vector with the current velocity of the mesh node;

- *ExtractBeacon*: This function performs several *Gets* in the Packet to extract the information that has been placed on the beacon in a tag. It will be responsible for getting the values of the position and velocity of the sender mesh node, the IP address of that node, the time of received beacon, the correspondent MAC Address, and the number of hops.

At the receptor of one beacon, each STA on the mesh interface will have available the following information:

- MAC Address: The MAC Address of the sender mesh node;

- Time Beacon: The time of the last received beacon from that mesh node;

- RSS: The RSS value associated to the received beacon;

- Position Sender: The current position of the sender mesh node;

- Velocity Sender: The current velocity of the sender mesh node;

- Position STA: The current position of the STA;

- Velocity STA: The current velocity of the STA;

- Number Hops: The number of hops through that mesh node;

- IP Address: The IP address of the mesh interface.

Now that all these parameters are available on each STA, the *callback* method was used in order to transfer these parameters to the connection manager.

One problem that appeared in the mesh module was the possibility of a set of nodes entering a loop state, which could be explained in these steps:

- One node connects through an AP through the Wi-Fi or the DSRC interface;

- It starts sending beacons in the mesh interface;

- Another node, that does not have any infrastructure at range, receives the beacon from the first node and starts itself to send beacons through the mesh interface;

- Meanwhile the first node gets out of range of the infrastructure, but instead of stopping sending beacons in the mesh interface, it detects the other node that is also sending beacons and continues sending beacons without any infrastructure to support it;

- Both nodes enter a loop state providing connectivity to each other, but not to the infrastructure.

  In order to fix this problem, the origin MAC Address that caused the start of the beacon was added to the beacon, and it is used in the receiver in a comparison function. When the origin MAC Address is equal to the address of the own node, it stops sending beacons.

Fiqure 4.4 depicts the mesh looping problem. First of all, the vehicle A is connected through an infrastructure unit **(1)** and is sending beacons to the vehicle B **(2)**. After receiving the beacons from the vehicle A, the vehicle B starts also sending beacons **(3)**. After a certain time and due to the mobility of vehicles, the vehicle A is no longer at range of the infrastructure point. However, since it is receiving beacons from the vehicle B **(5)**, it is also sending beacons to him **(4)**, providing an unreal connectivity to each other.

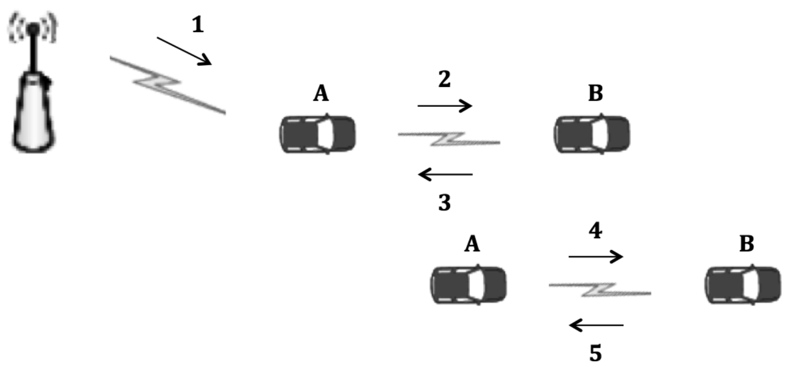


Figure 4.4: Mesh looping problem

4.4.5 Callback Method

The goal of the *callbacks* is to allow that, in one specific module, a function/method be called without any specific inter-module dependency. Therefore, four *callbacks* were implemented with different purposes:

- **Callback1**: This *callback* is used to transfer the parameters from the STA class to the connection manager. When a node receives a beacon in the Wi-Fi, DSRC or in the cellular interface, this *callback* will be activated and the parameters will be available in specific functions created in the connection manager.

- **Callback2**: This *callback* is also used to transfer the parameters from the STA class to the connection manager, but this time regarding to the mesh interface. Therefore, when a node receives a beacon in the mesh interface, this *callback* will be activated and the parameters will be transferred to the specific functions created in the connection manager.

- **Callback3**: This *callback* is used to transfer the decision provided by the connection manager to the STA class to force the connection to the choosen AP at MAC layer.

- **Callback4**: This *callback* is used to transfer information to the *MeshWifiMac* module regarding the state of the node, which is connected to an infrastructure unit or not.

Figure 4.5 shows a schematic representing the callbacks method.

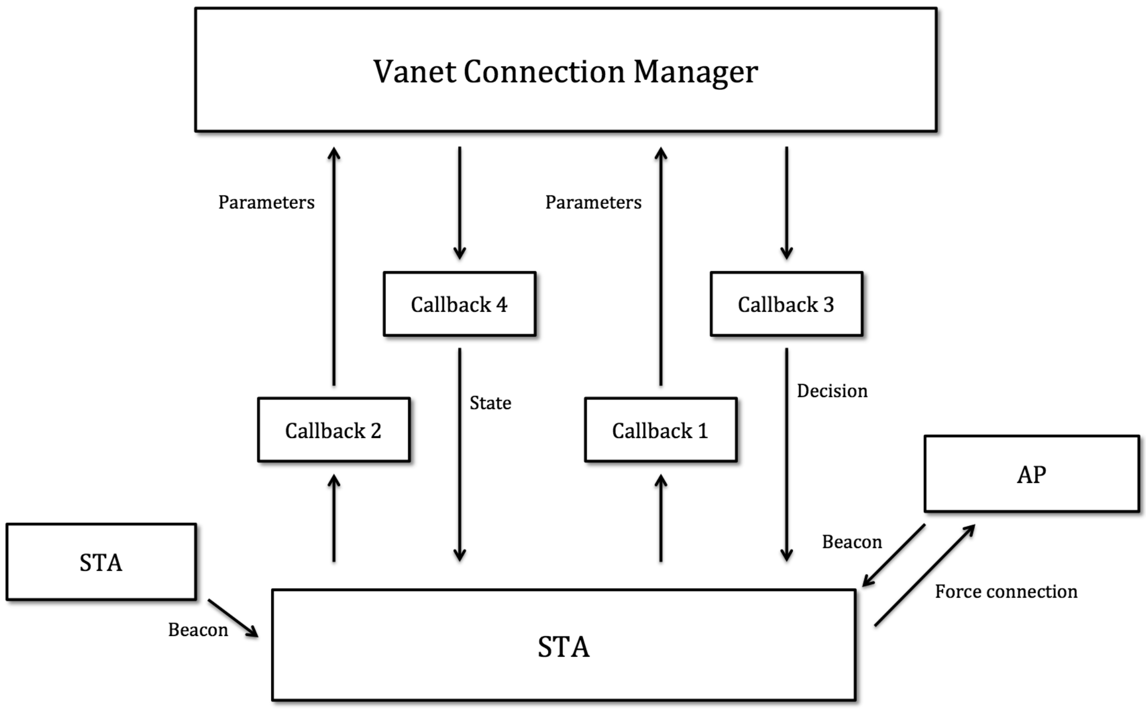


Figure 4.5: Callback communication scheme

The vehicle has four different interfaces, one for each technology. As previously referred, the AP class in the *WifiMac* is responsible for the IEEE 802.11p, IEEE 802.11g and cellular network, in the case of the mesh interface is modulated by the *MeshWifiMac*. Therefore, when one vehicle receives a beacon, a *callback* it will be activated according to the wireless interface, transfering the parameters to that candidate to the connection manager. The connection manager processes that information and select one candidate, activating another *callback* with the chosen MAC Address or simply transfer the information regarding to the state of the mesh node (if it is connected or not).

4.4.6 IP Layer

The IP layer will be very important in the performance of our simulation in terms of controlling the access technology to establish the connection. Since there is one network for each techonology aggregated by a router, connecting to the server node in a separate network which intends to represent the Internet for example, we need to provide the right path from the vehicle to the server node, according to the connection manager decision.

For that purpose, we adopted the static routes method which intends to give information to vehicles related to next hop to reach the server node. Therefore, in the creation of the scenario, we defined static routes for each technology as shown in Figure 4.6, with equal metrics for each path, providing the routing needed to the server node. With the assigned metric, we give to the STA node the next hop according to the metric, in order to reach the server node in the 10.0.1.0 network.

The connection manager will perform the decision, and according to its decision, it is assigned a lower metric to the wireless interface of the chosen technology. Therefore, the traffic will flow to the server node through the chosen interface.

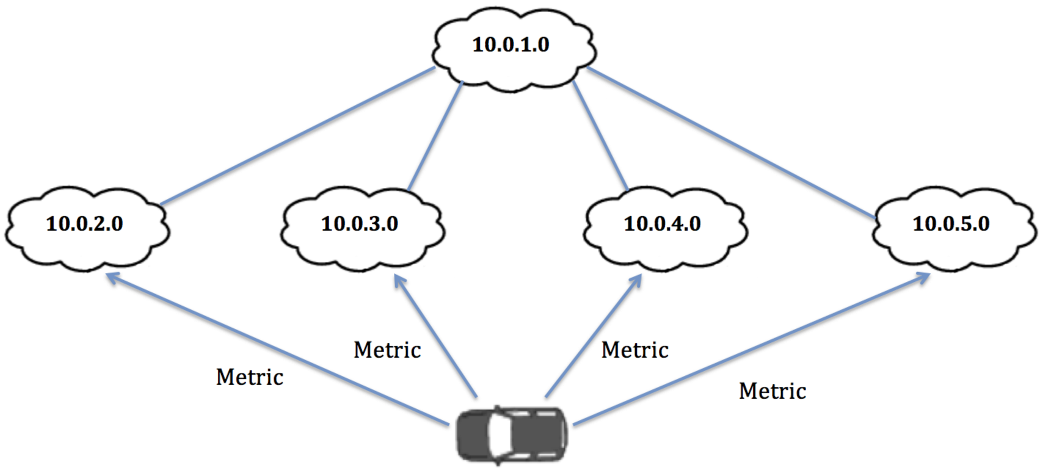


Figure 4.6: Static Routing

Regarding the mesh network, a lower metric is assigned to the 10.0.5.0 network, forwarding the data until the next vehicle. Moreover, the connection manager installed on that vehicle will also perform a decision until the server node.

4.4.7 Traffic Application

To evaluate the implemented connection manager in terms of data loss, a traffic application was required. therefore, we chose the traffic application UDP, provided by the NS-3 simulator, which was choosen due to its simplicity and efficiency.

The UDP application is installed on each node in the scenario being configured to send 1024 bytes packets at a range of 0.01s to the server node (which is located in a separate network). Thereby, according to the decision of the connection manager, each vehicle must be connected through an infrastructure to reach the server node. By intercepting the packets at the MAC layer it is possible to count the number of packets sent by each wireless interface of the node and thereby the percentage of packet loss, by performing the difference between the total data sent and the received data.

The connection manager is an application totally independent of the traffic application. The UDP is always sending data, not concerning with the handovers and the data loss, which are functions of the VCM. Thereby, the VCM must be capaple of antecipating where to connect preventing at most the data loss.

4.5 Vanet Connection Manager

4.5.1 Implementation

In terms of implementation, the VCM, was created as an application that is installed on all vehicles of the scenario, providing the necessary intelligence for the network selection. This application receives and processes all local information from each vehicle, and therefore, it combines the information and decides according to priority values. With the modifications previously presented on the STA and in the Mesh class, the connection manager will automatically receive all the current available parameters whenever the node receives a beacon. Therefore, it performs a constant analysis in order to choose the best available candidate and the best network to each vehicle in the transition state of the simulation. This application is initiated 1 second after the simulation starts (to avoid rushed decisions), and it is always enabled until the simulation ends.

The functions of the connection manager can be explained in these main steps:

- The vehicle receives a beacon from an AP (Wi-Fi, DSRC or Cellular interface) or from other node (Mesh interface);
- The beacon contains local information that will be processed on the STA/Mesh class;
- The *callback* method is activated and the local information goes to the specific functions in the connection manager;
- The connection manager processes the information and takes an informed network decision;
- According to that decision, a lower metric is set to the IP route according to the chosen technology;
- In the case the decision is a Wi-Fi, DSRC or the Cellular interface, another *callback* is invoked, but this time in the opposite way, providing the choosen MAC address to the STA class in the MAC layer.
- The STA class receives that information and forces the connection through the selected AP.

Although the connection manager is an unique application that is installed on each vehicle, the implementation was divided into three main modules, each one with specific purposes: **Scanning module** responsible for gathering data from each candidate and organize it, **Decision module** responsible for assigning the priorities to each candidate, according to the parameters, and **Connection module** responsible for establishing the connection through the choosen candidate.

4.5.2 Scanning Module

The main purpose of this module is to collect and organize all the data that comes from the MAC layer, through the *callback* method. As previously referred, when the STA receives a beacon, the correspondent *callback* is activated and the local information of that interface is transfered to the connection manager, which means that data will arrive there, coming from the four wireless interfaces available on the vehicles.

Each wireless interface is associated to one distinct *callback* in order to distinguish the received data according to the technology. Therefore, when a specific *callback* is activated, it will call the corresponding function *InfoG*, *InfoP*, *Info3G* or *InfoMesh* that will be responsible for the process and identification of the data.

The method implemented to organize all the received data was a C++ list of structures called $< InfoList >$. Each STA has its own list, which contains all the information related to the candidates for connection. This list has as key element the MAC Address to identify the candidate, and for each candidate, it contains information such as the position and speed (in case of being a mesh node), the signal quality, the time of the received beacon, the number of connected nodes and the number of hops (also in case of being a mesh node), and a parameter which identifies the technology which be used in the next module of the connection manager.

$< InfoList >$ will be filled according to the access technology by the developed functions *InfoG*, *InfoP*, *Info3G* or *InfoMesh*. These functions will access the received values, check if the received MAC Address already exists in $< InfoList >$ and update the values corresponding to that address or proceed with a new insertion containing all the information related to the detected candidate, as shown in Figure 4.7.

At this point, $< InfoList >$ contains all the possible candidates for each STA along with their information. Therefore, in the end of the developed functions *InfoG*, *InfoP*, *Info3G* and *InfoMesh*, a new function is called, the *InfoNet* which will be responsible for the network selection.

4.5.3 Decision Module

In the previous phase of the connection manager, the data of each candidate was organized according to its technology in the < InfoList > by the developed functions *InfoG*, *InfoP*, *Info3G* and *InfoMesh*.

The *InfoNet* algorithm will be responsible for processing all the data contained in < InfoList > and identify the best connection available for each vehicle, according to its priority values.

As previously referred, the proposed network selection mechanism is based on an AHP that combines various networks, preferences and geographic inputs to determine which of the available networks is more indicated for each vehicle. Thereby, in order to choose the best connection available, we need to determine the priorities to evaluate the highest priority network.

With the criteria identified for the network selection through the AHP in Chapter 3, we need to have access to all of those parameters in the connection manager in order to determine the priority of the network candidates.

Some parameters for the assigning of priorities such as the RSS value, the number of connected nodes and the number of hops are already available in *InfoNet*; however, we need to calculate the expected contact time using the geographic inputs and attribute the price

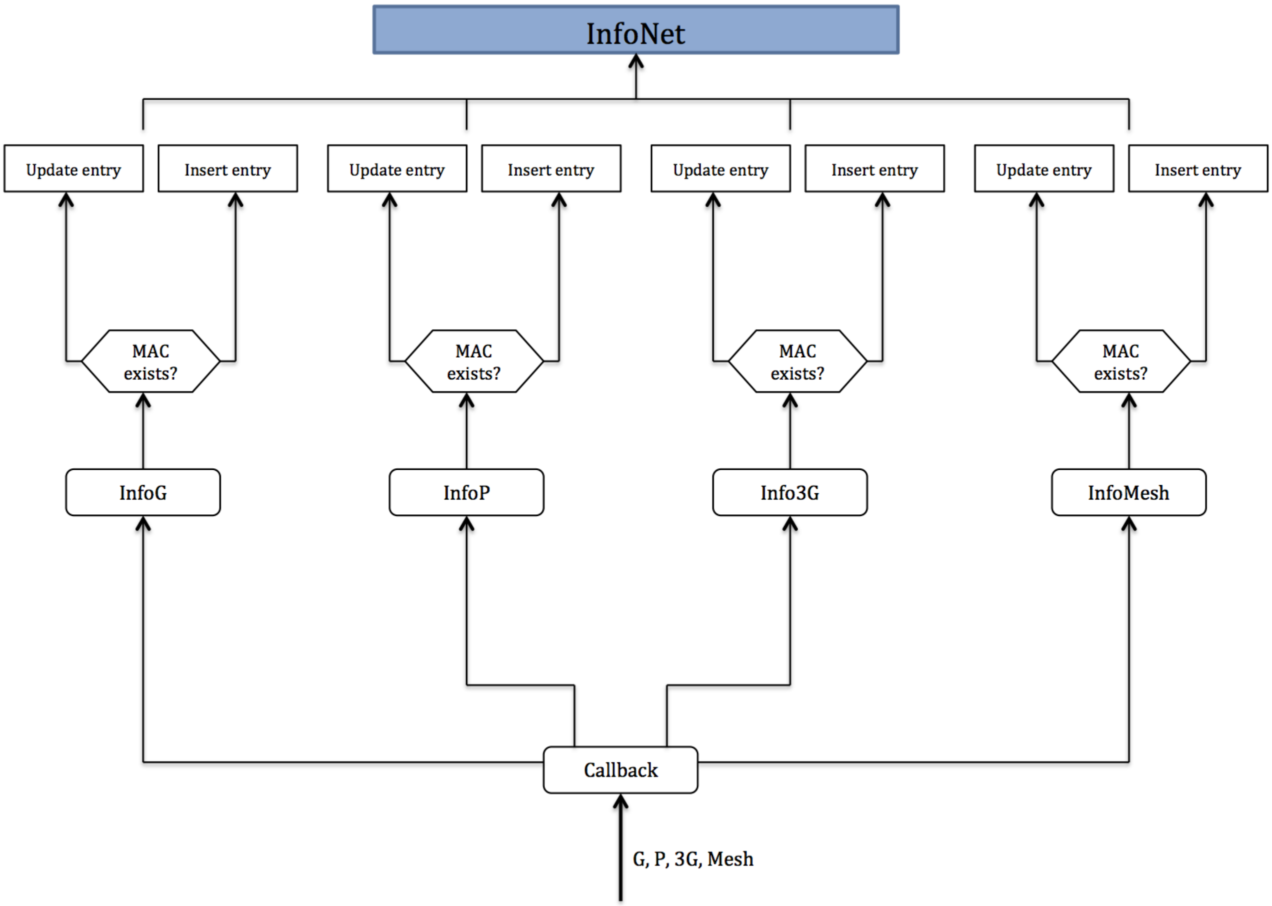


Figure 4.7: Scheme Scanning module

value according to the technology (the only technology who is not considerated free is the cellular).

In order to calculate the expected contact time of each network candidate, the following process has been used according to [91]. It takes into account the current position of the nodes and also the relative speed. The authors concluded that the duration of the communication between two nodes is given by Equation (4.2).

$$t = \frac{-(a \cdot c + b \cdot d) \pm \sqrt{(c^2 + d^2) \cdot R^2 + (b \cdot c - a \cdot d)^2}}{c^2 + d^2} \tag{4.2}$$

$$a = x_j(0) - x_i(0) \tag{4.3}$$

$$b = y_j(0) - y_i(0) \tag{4.4}$$

$$c = v_j \cdot cos(\theta_j) - v_i \cdot cos(\theta i) \tag{4.5}$$

$$d = v_j \cdot sin(\theta_j) - v_i \cdot sin(\theta i) \tag{4.6}$$

Figure 4.8 shows the physical model notation where $x_i(0)$ and $y_i(0)$ represents the initial position of the first vehicle, $x_j(0)$ and $y_j(0)$ represents the initial position of the second vehicle,

v_i and v_j represents their velocity and θi and θj represents their angle with the plan.

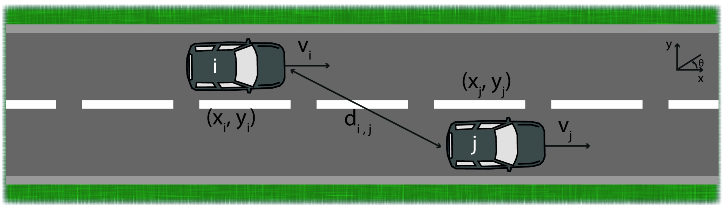


Figure 4.8: Physical model notation, in [91]

According to the returned values of the GA for the level 2 and 3 of criteria, the *InfoNet* will be responsible for automatically filling for each possible candidate the correspondent priorities related to each candidate: the RSS, the number of hops to reach the service provider, the expected contact time, the availability and the price associated. Figure 4.9 exemplifies the behavior of the *InfoNet*. For all candidates, it will apply priorities according to the candidate values, which are in level 4 (Set of alternatives), multiplying by the level 3 and 2 of the returned values of the GA, achieving thereby the final priority for each candidate, Equation 4.5.3.

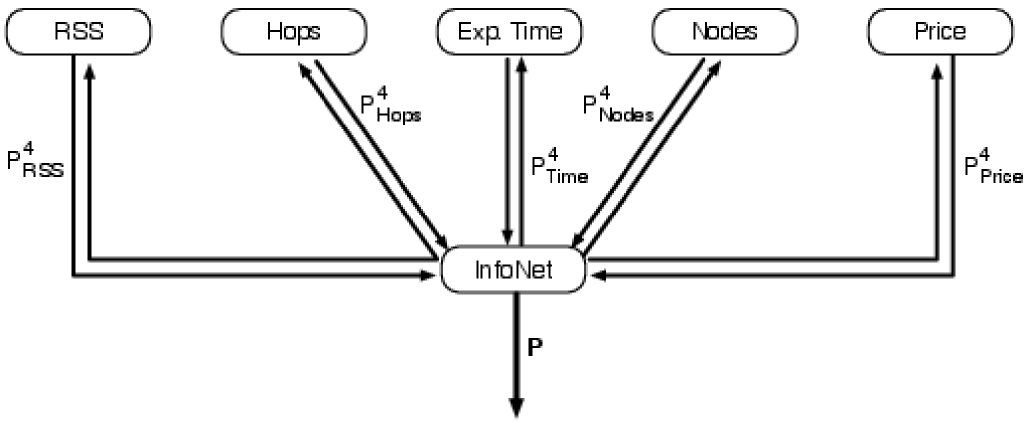


Figure 4.9: InfoNet scheme

$$\text{Priority} = \mathrm{P}^2_{Price} \times P^4_{Price} + P^2_{RSS} \times P^4_{RSS} + P^2_{Backdrop} \times P^3_{Nodes} \times P^4_{Nodes}$$
$$+ \mathrm{P}^2_{Backdrop} \times P^3_{Hops} \times P^4_{Hops} + P^2_{Backdrop} \times P^3_{ExpTime} \times P^4_{ExpTime}$$

4.5.4 Connection Module

In this phase, where each possible network candidate already has the final priority calculated in the previous phase, the best candidate is chosen.

< InfoList > has now not only the values from the MAC layer but also the priority values filled in the decision module. The function *Decide* will sort the < InfoList > according to the final priority value but it will take into account the hysteresis value also returned by the GA. The value of the hysteresis (between 0.05 and 0.1) will ensure that, when a technology and network are elected, they will not be superseded in the very next moment by the previous selection due to an occurence of a small variation in the priority.

Therefore, after the election of the best network candidate, two main actions must be performed:

- Force the connection in the MAC layer to the selected MAC Address through the SSID;
- Force the traffic to the selected network through the static routes, assigning the lowest metric.

In order to establish the connection to the selected infrastructure point, a *callback* is issued from the connection manager to the STA class in MAC layer transfering as parameters the selected candidate and the technology associated. This result is used to check in the STA class if the selected infrastructure point is already connected, and if it is not, force the connection.

In order to establish the connection through the selected network, the connection manager removes all the static routes to the server node, creating new ones, but this time with the lowest metric for the choosen technology forcing the traffic from the UDP application to flow through that network.

4.6 Traditional Connection Managers

The best way to observe the enhancement provided by the VCM is to test it under the same conditions of other network selection mechanisms. However, there are no connection managers that, on the one hand, operate in this infrastructure architecture with IEEE 802.11p RSUs, Wi-Fi hotpots, cellular network and even with the possibility of mesh networks are available, and on the other hand, that face the VANET characteristics. Therefore, we proposed to define and implement two connection managers with different characteristics, typically used in other wireless environments:

- **Basic Connection Manager (BCM) -** This simple network selection mechanism only takes into account the signal quality of the link to make a decision. It will compare all the RSS values from the possible candidates and choose at any time the candidate with the highest value. This network selection mechanism only uses the cellular network whenever no other solution is available.
- **Preference-based Connection Manager (PCM) -** This network selection mechanism is more advanced than BCM, it takes into account the user preferences combined with the RSS value from the possible candidates. This version of the connection manager will always prefer the IEEE 802.11p technology over the IEEE 802.11g and the cellular. In the case of having at the same time more than one possible candidates of

the same technology, it will choose the one with higher RSS value. As BCM, it will only use the cellular network whenever no other solution is available.

These connection managers were implemented to evaluate the improvement brought by the proposed connection manager, the VCM, in urban environments.

4.7 Summary

After explaining all the conceptual work related to VCM, in this chapter we proceeded with the implementation of the proposed solution in simulation environment. We started with a brief description of the existing modules in NS-3, such as the PHY and MAC layer, which were used for our implementation. In Section 4.3 we presented the logical architecture used in order to implement and evaluate our connection manager. It intends to emulate a possible infrastructure deployment scheme where several vehicles are equipped with four wireless interfaces, one for each present technology, with communication capabilities. Therefore, we proceeded by justifying the choices performed in the existing modules of NS-3 and also all the performed modifications, such the created functions, the callbacks, the static routes and the multi-hop extension, in Section 4.4.

In the followed section, we presented the methodology used in the implementation of our connection manager, explaining in detail the three modules implemented: scaning, decision and connection modules.

In order to observe the enhancements provided by our connection manager, we implemented two traditional connection managers, the BCM that only considers the quality of link for the election process,and the PCM which takes into account the users preference besides the RSS.

In the next chapter we will procceed with the priorities calculation and their validation, following with an evaluation of our connection manager, while compared with the typical connection managers in different urban scenarios.

Chapter 5

Results

5.1 Introduction

After presenting a description of the proposed connection manager, explaining the conceptual part and the implementation of the network selection mechanism, we now proceed with the evaluation in the simulation environment.

We now present, for the priorities determination using the speed for pre-selection, three comprehensive scenarios including Wi-Fi APs, 802.11p RSUs, and cellular network, strategically deployed, in order to maximize the amount of real-world situations that may occur in Section 5.2. To ensure that the obtained results are not tied to the developed scenarios, we proceed to a validation with the evaluation in randomly deployed infrastructure scenarios in Section 5.3.

In Section 5.4, a Manhattan grid scenario is used, resorting to SUMO, consisting in vehicles with turn probabilities and car-following model, which circulate randomly across the scenario with top speed of 50 km/h, to perform the global evaluation of the developed connection manager in terms of amount of data transmitted through each technology, data loss and number of performed handovers.

To observe the enhancements provided by our connection manager, we used the two connection managers implemented in previous chapter, as baseline.

All presented results are obtained through the mean of 10 simulations with confidence intervals of 95%.

5.2 Priorities Determination

In Section 3.5 a set of criterion for the AHP was proposed accounting on speed for pre-selection. As previously mentioned, it may be intuitive to determine some of the priorities of the AHP; however others are not so straightforward. Therefore, it is impossible to determine them manually in order to obtain the optimized output, due to the large number of criteria. Therefore, the GA was used along with the NS-3 simulator to calculate the optimized priorities for the AHP, as explained in Section 3.6.

Three similar scenarios were used in order to achieve the optimal priority values for each of the pre-determined categories of speed. All scenarios were composed by 5 vehicles with pre-defined trajectory, and the variations performed were in terms of the speed of the vehicle and the infrastructure density, according to the requirements of each category.

The implemented scenarios were divided into 2 different zones, each one with different coverage conditions. This distinction between the 2 zones of the scenarios allows, on the one hand, for the sharpening of the capacity of dealing with a high amount of possible connections, and on the other hand, to create the obligation of dealing with scenarios where the most preferable technology is not available, dotting the VCM with more resilience to these cases.

5.2.1 Moving Fast

Figure 5.1 shows the scenario used to obtain the optimal priorities for the vehicles traveling with speeds ranging from 10 to 30 m/s. Due to the high speed of nodes, it is expected that they do not connect to the Wi-Fi infrastructure, but try to take the most profit of the deployed IEEE 802.11p RSUs. The cellular network is expected to be used in cases where it reveals a better option above all the candidates, filling the user requirements, and when that fact compensates the associated price.

In the first part of the scenario all technologies are available, which is the most common case. Regarding to the second part of scenario, it is only possible to find Wi-Fi hotspots and cellular technology leading to VCM to choose between these two, in around 300m.

In terms of deployed infrastructure, in the first part 20 RSUs were placed strategically together with 40 Wi-Fi hotspots in order to provide full connectivity. In the second part of the scenario the amount of infrastructure deployed was reduced to 15 Wi-Fi hotspots uniformly distributed.

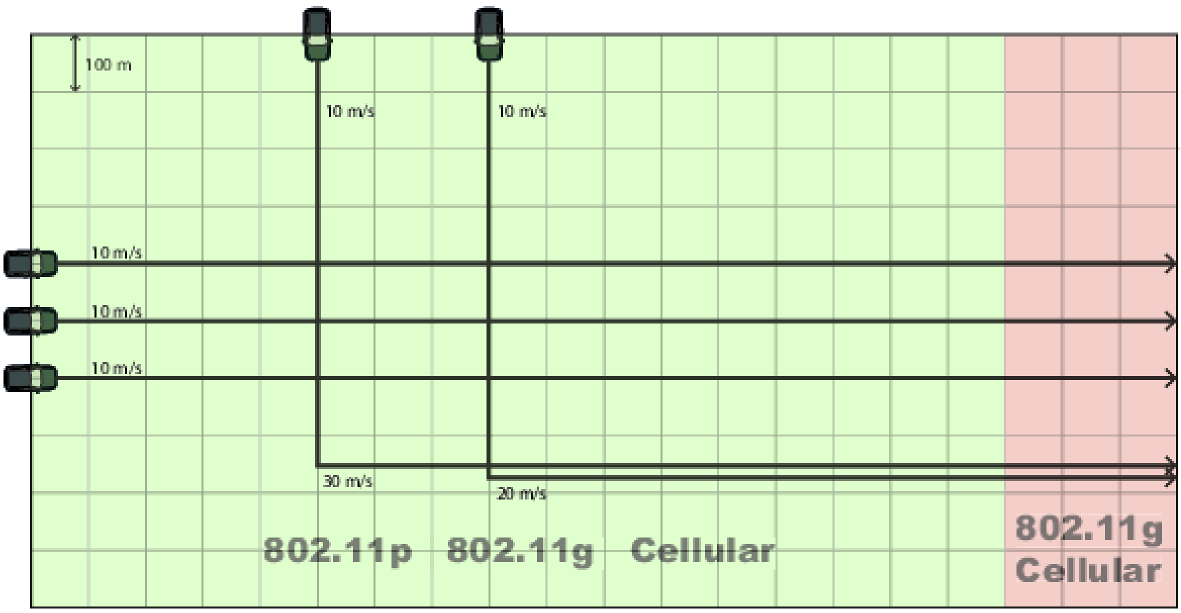


Figure 5.1: Moving Fast Scenario

5.2.2 Moving Slowly

Figure 5.2 shows the scenario used to obtain the priorities for moving slowly vehicles where their speed ranges from 5 to 8 m/s.

Contrarialy to the previous case, due to the speed of vehicles, it is expected that nodes connect to Wi-Fi infrastructure mainly when the expected contact time is large but still with some restrictions. It is expected that the nodes take the most profit of the deplo볼ded IEEE 802.11p RSUs and rely on the cellular network only to complement the connectivity.

In what concerns the infrastructure distribution, in the left part of the scenario there are 16 RSUs strategically placed and 40 Wi-Fi hotspots randomly spread in order to guarantee an excessive network coverage, forcing the VCM to choose the best APs while minimizing the number of handovers. In the other side of the scenario, the IEEE 802.11p is no longer available, but 30 Wi-Fi hotspots were deployded around 500 m to guarantee an excessive coverage as well.

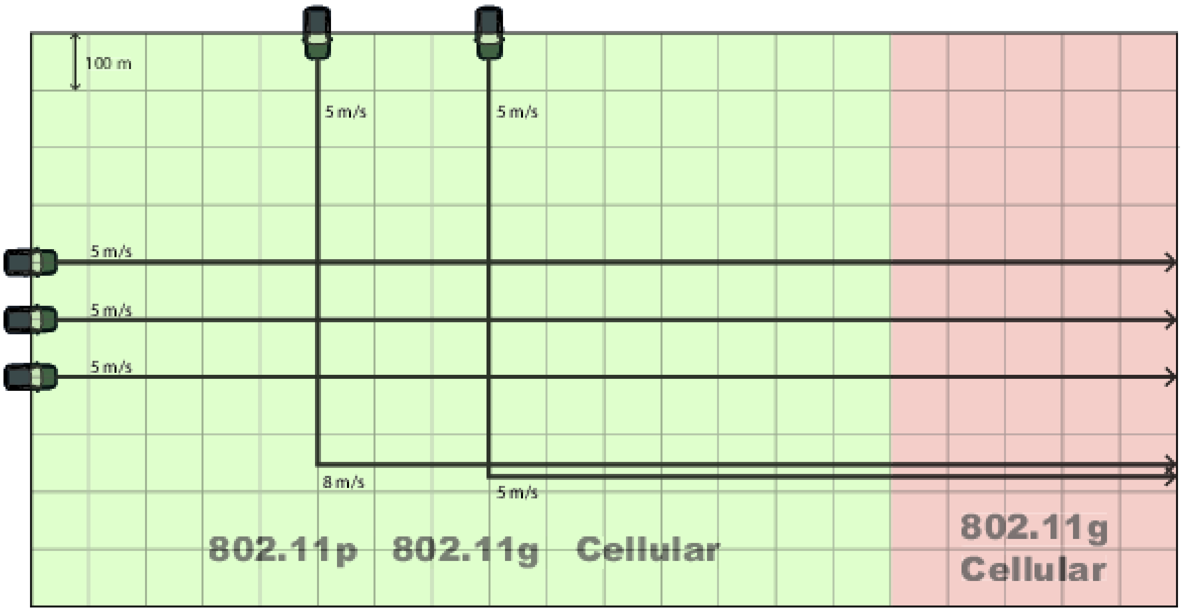


Figure 5.2: Moving Slowly Scenario

5.2.3 Stopped/Very Slow

Finally, Figure 5.3 shows the scenario used to obtain the optimal priorities for vehicles with very low speed or even stopped.

Due to the lower speed of vehicles, it is expected that they take the highest profit of the deployed infrastructure, relying in the cellular network in the extreme case of having no other candidates available.

Regarding the deployed infrastructure, it is the same of the previous case: in the left part of the scenario, 16 IEEE 802.11p RSUs are strategically placed and 40 Wi-Fi hotspots are spread across the area, providing an excessive coverage. In the right part of the scenario, 30 Wi-Fi hotspots were uniformly deployed, providing coverage as well, but only through IEEE 802.11g technology.

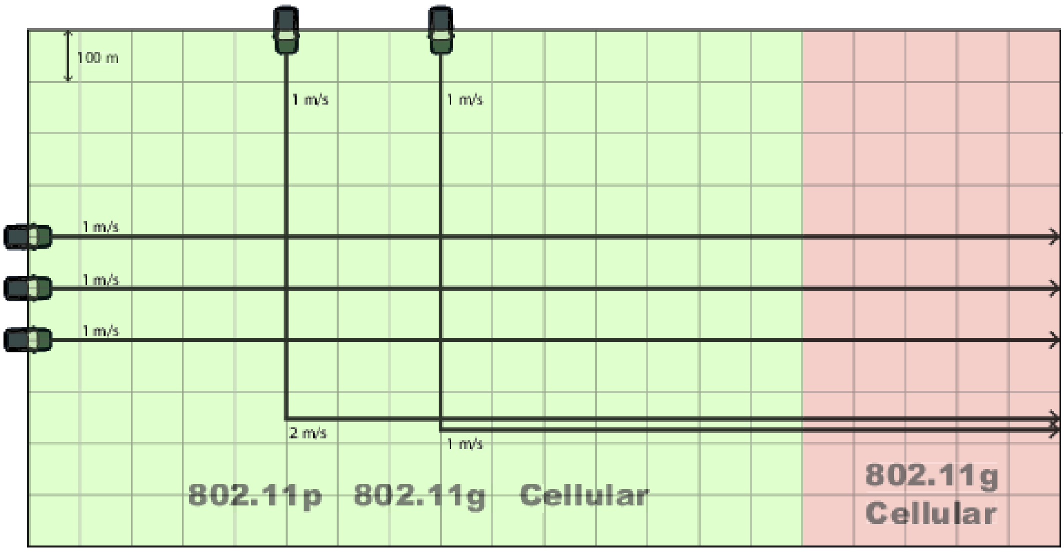


Figure 5.3: Stopped/Very Slow Scenario

5.2.4 Optimal Priorities

After a description provided in the last section, where the adopted methodology for the priorities calculation was explained, the results obtained through the GA are shown in Figure 5.4, where each bar shows the priority for each category of speed (Table 3.2).

Analysing the Figure 5.4, it is possible to see that the priority relative to the criterion price decreases with the increase of speed. This result is reflected in the reduction of the number of preferable candidates: the faster the vehicles move, the less the Wi-Fi technology becomes preferable, which is explained by the short coverage and the reduce expected contact time.

The priorities relative to price for the user and for the operator, are related to economic characteristics and have no relevance for our study, therefore we leave them off on the evaluation of the GA, considering them 0.5.

From another point of view, the backdrop values increase with speed, showing that a faster vehicle will prefer to look into the expected contact time, leaving the price behind, in order to decrease the number of handovers and the inherent data loss. Taking a look at the backdrop values, it is possible to conclude that the expected contact time along with the number of hops dominate over the availability, specially for higher speeds.

An interesting value is the RSS value. In traditional connection managers, this value is highly take into account for the network selection problem; however, for the VCM, it is the one with least priority in the overall decision, which is explained by the abundance of usefull parameters that are being provided to the decision. It has the higher value for moving slowly vehicles, which is the intermediate case.

In Table 5.1 we present the values of the hysteresis provided by the GA. It is possible to conclude that, for higher speeds, the hysteresis value increases, which is explained by the fact that vehicles moving at lower speeds have a better perception of the changes in the environment than those who move with higher speeds.

The optimal values of priorities were obtained for each category of speed, which means that VCM will automatically detect the vehicle speed and according to that speed it will

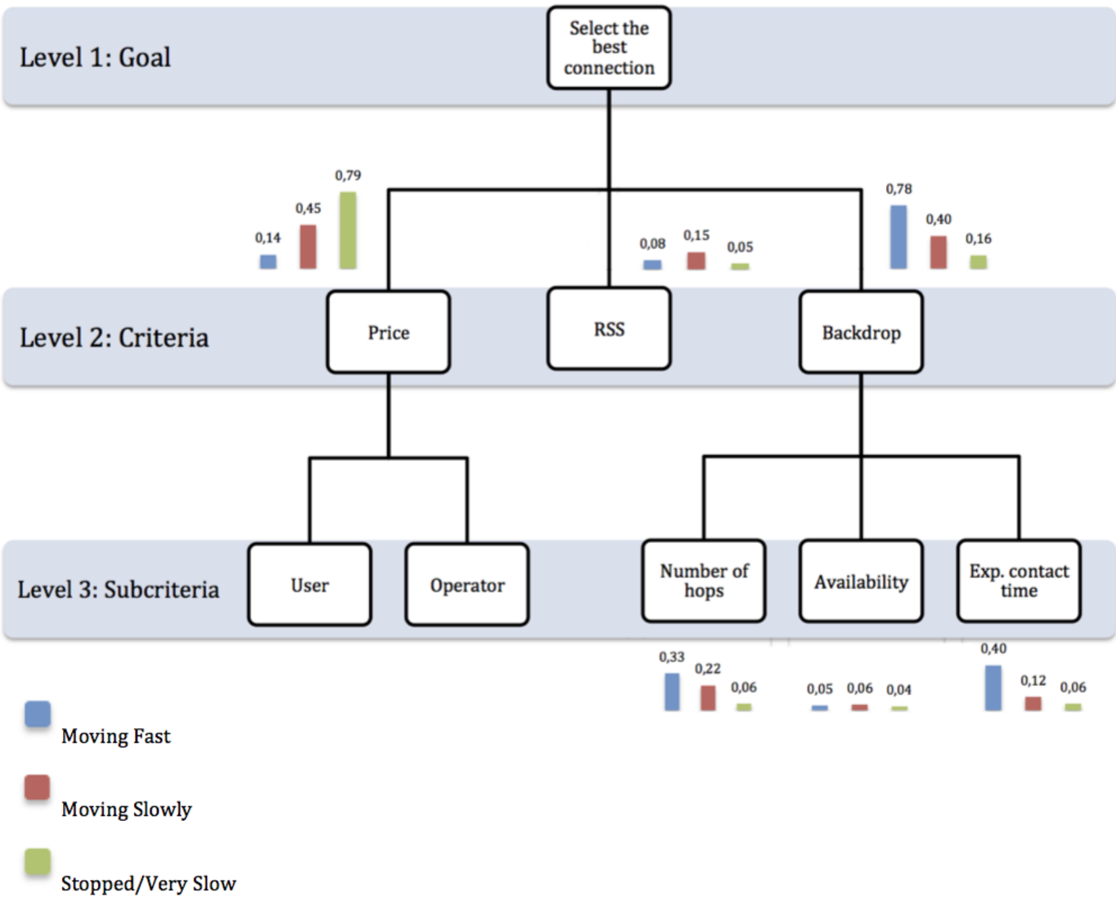


Figure 5.4: AHP obtained Priorities

apply the correspondent priority values. The process is competely transparent for the user.

Table 5.1: Hysteresis Values

Categories	Hysteresis
Moving Fast	0.104
Moving Slowly	0.103
Stopped/Very Slow	0.055

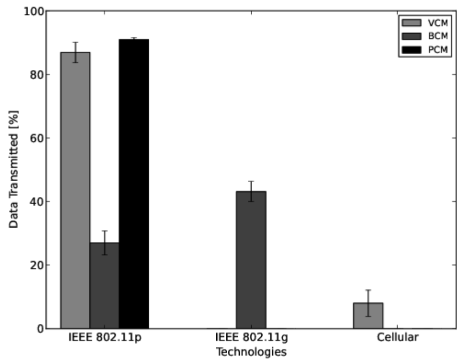
5.3 Priorities Validation

In the previous section, the optimal values of priorities were determined. Before testing the VCM in a completely random scenario, we need to validate the priority values for each of the vehicle categories previously presented, to ensure that they are not tied to the scenarios used for their validation, performing an evaluation with random infrastructure deployed.

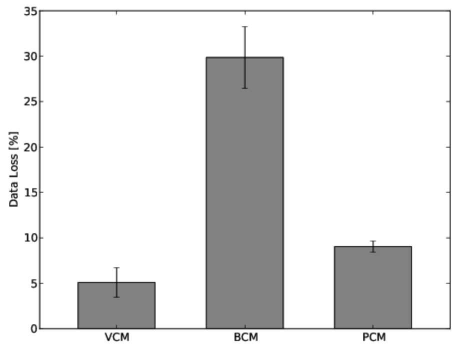
The following results are a comparison between the 3 connection managers in terms of the amount of data transmitted through each technology, data loss and number of performed handovers.

Using as starting point the previous scenarios, some modifications were perfomed in terms of the deployed infrastructure. This time, there are 15 IEEE 802.11p RSUs and 50 Wi-Fi hotspots placed randomly. The mobility model presented by the vehicles is maintained.

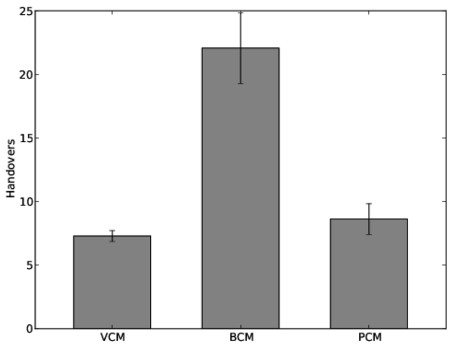
5.3.1 Moving Fast



(a) % Transmitted Data for Technology



(b) % Data Loss



(c) Number Handovers

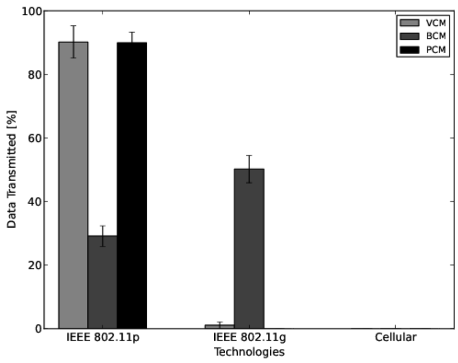
Figure 5.5: Results - Priorities Moving Fast

The results presented in Figure 5.5 are relative to the **Moving Fast** vehicles. Since the main characteristic is the high velocity presented by the nodes, it is expected that they use IEEE 802.11p technology with the highest preference. On the other hand, the Wi-Fi technology will not be a good alternative due to the short range and the association time of 2 seconds required, leading to an increase in terms of packet loss.

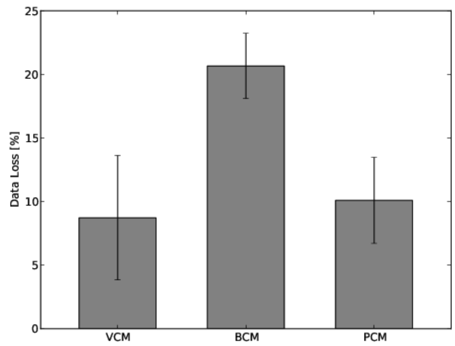
In Figure 5.5(a) it is possible to observe that VCM does not use the Wi-Fi technology to send data, contrarily to the BCM. This fact is explained due to the node speed, since VCM at higher speeds does not try to connect to an infrastructure with small expected contact time. This leads, in terms of data loss, that VCM has better values while comparing to the

BCM, as it can be seen in Figure 5.5(b). On the other hand, VCM sends more data through the cellular network (Figure 5.5(a)), which is in accordance with the fact that it performs less handovers while compared to the other connection managers (Figure 5.5(c)) and even less data loss (Figure 5.5(b)). This shows that VCM has given more preference to perform less handovers, and also to try to reduce at most the data loss, even if that costs a litle more to the user.

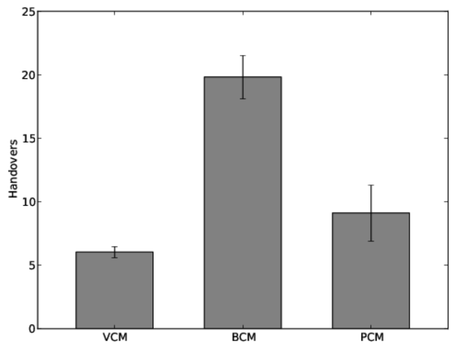
5.3.2 Moving Slowly



(a) % Transmitted Data for Technology



(b) % Data Loss

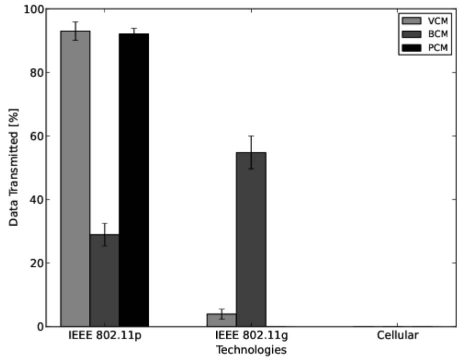


(c) Number Handovers

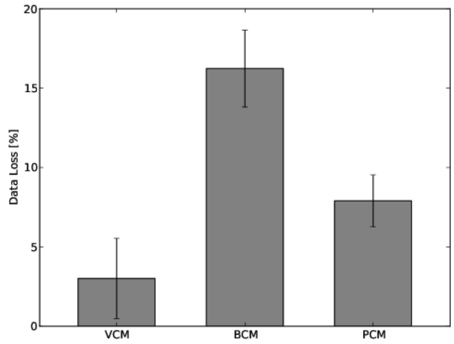
Figure 5.6: Results - Priorities Moving Slowly

The results presented in Figure 5.6 are relative to the **Moving Slowly** vehicles. In this scenario, the node is moving with an average speed of 5m/s, which means that it is able to connect to Wi-Fi and IEEE 802.11p, giving priority to the latter due to the higher expected contact time. In Figure 5.6(a), it is possible to see that VCM has almost the same behaviour as the PCM in terms of the transmitted data for each technology avoiding IEEE 802.11g and the cellular. In terms of data loss, VCM is much improval when compared to BCM and slight improvement when compared to PCM (Figure 5.6(b)). In terms of handovers, the VCM is able to perform less handovers when compared to the PCM and much less then BCM (Figure 5.6(c)).

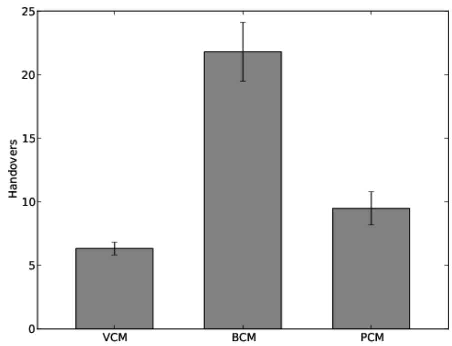
5.3.3 Stopped/Very Slow



(a) % Transmitted Data for Technology



(b) % Data Loss



(c) Number Handovers

Figure 5.7: Results - Priorities Stopped/Very Slow

The results presented in Figure 5.7 are relative to the **Stopped/Very Slow** vehicles. Since the main characteristic is the low velocity of nodes, it is expected that it uses IEEE 802.11p and Wi-Fi technologies in order to avoid at most the cellular network, reducing the price for the user. In Figure 5.7(a), it is possible to see that VCM has a similar behavior when compared to PCM in terms of transmitted data per technology. BCM sends more than 50% through Wi-Fi technology which explains the high value for data loss. VCM has better results in terms of data loss while compared with the other connection managers (Figure 5.7(b)).

On the other hand, VCM has also better results in terms of handovers among all of them, as shown in Figure 5.7(c).

5.4 Global Evaluation

In the previous section we performed a validation of the priorities for each category of speed obtained through the GA using an evaluation under similar scenarios but with randomly infrastructure deployed, ensuring that the priorities of VCM are not tied to the scenarios used for their calculation.

As previously mentioned, VCM automatically detects the vehicle speed, and according to that value, it applies the correspondent priority values, obtained in Section 5.2.

It is now mandatory to evaluate the proposed connection manager in completely general scenarios. For that purpose, as mentioned in Section 2.11, the mobility model simulator chosen was SUMO [79]. It has been used to generate a Manhattan grid with 1.4 km^2 and 400m between roads. According to the scenario, a certain amount of vehicles is introduced in the grid and circulate with equal turn probabilities (25% for each side), using the simulator's car-following model. Vehicles queue at intersections, creating real situations where they slow down while approaching the intersections. There are no traffic lights available and the top speed is 13.9 m/s (50 Km/h), since it is a urban scenario.

The artificial losses introduced in Section 4.4 were removed to observe the natural losses introduced by NS-3 between the 3 connection managers under evaluation. The simulation time is 300s, which is enough taking into account the connectivity period of vehicles.

For the evaluation of the connection manager, the vehicle density and the amount of deployed infrastructure was varied according to the Table 5.2 and the Table 5.3.

Table 5.2: Vehicle's Density

Density	**Veh**/km^2
Low	3.47
Moderate	13.89
High	20.83

Table 5.3: Infrastructure Density

Technology	**Infrastructure+**/km^2	**Infrastructure-**/km^2
IEEE 802.11g	50	21.42
IEEE 802.11p	14.28	4.28

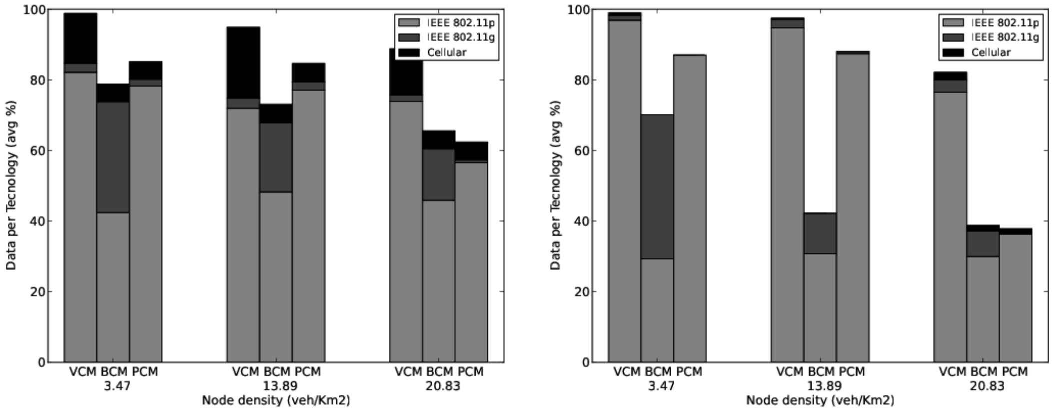
The following sections present a comparison between the 3 connection managers, in terms of amount of data transmitted through each technology, number of handovers and data loss.

5.4.1 Data per Technology

Figure 5.8 shows the percentage of transmitted data through each technology for all the connection managers, varying the deployed infrastructure and the vehicle density. The confidence intervals are ommited in this plot, for the sake of perception, but they have the same values as before.

For all connection managers, IEEE 802.11p was the most preferred which coincides with the expected, due to the highest transmission range, hence the best signal quality and expected contact time, at the lowest cost.

In Figure 5.8(a), VCM sends the highest percentage of traffic through cellular technology while compared to the other connection managers. It realizes that there is not enough coverage to send all the data through IEEE 802.11p, or even that it is not enough to provide the minimum QoS. However, instead of trying to send the data through the IEEE 802.11g infrastructure at high speeds, it connects to the cellular network to avoid losing data. This



(a) Infrastructure- (b) Infrastructure+

Figure 5.8: Transmitted data through each Technology

phenomenon is observed in BCM, which blindly connects to the infrastructure unit with the highest signal quality, losing more data.

In Figure 5.8(b), it is possible to observe that VCM and PCM had similar behaviors in terms of delivering almost all the data through IEEE 802.11p, since the coverage provided by this technolgy is higher. The usage percentage of cellular network is now reduced for the same reason.

VCM benefits from being able to select the infrastructure unit with the highest amount of available resources compared to the other connection managers. It is possible to see from the behavior of the PCM that, despite having an acceptable behavior with low density of vehicles, when it increases up to 20 Veh/km^2, it starts to lose a large amount of data due to the fact that it tries to connect to the same infrastructure points.

BCM has a great amount of data loss, which blindly connects to the infrastructure units with quality of signal, leading to the loss of data because of the availability, where several vehicles try to connect to the same infrastructure.

5.4.2 Handovers

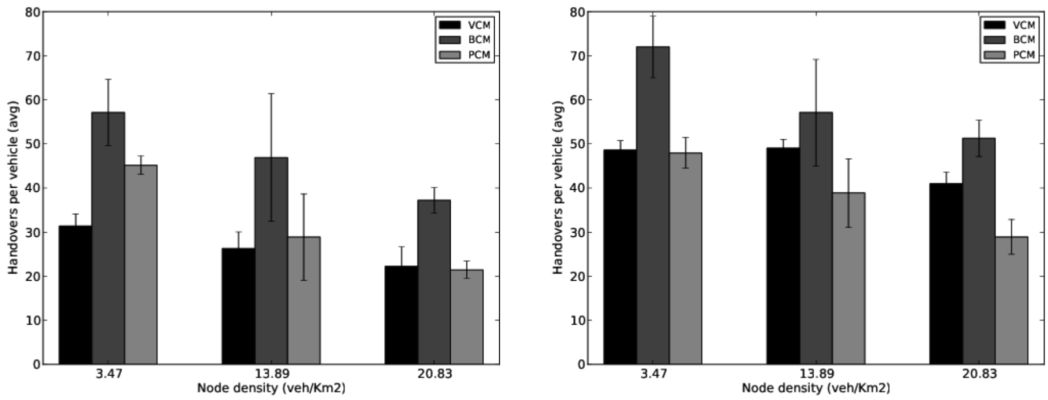
Figure 5.9 shows the number of handovers per vehicle for all the connection managers, performing the variation of the deployed infrastructure and the vehicle density.

In term of handovers, it is highly related with the quality of the link: it is expected that the lower the number of handovers performed, the stable the connection will be; however, it is not always that simple.

In Figure 5.9(a) it is possible to observe that the number of handovers performed by VCM is lower when compared to the other connection managers. However, with the increase of the vehicle density, it becomes equal to PCM. In order to avoid the most possible data, VCM prefers to perform some more handovers, achieving better results in term of delivery data.

In Figure 5.9(b) it is possible to notice a huge increase in terms of handovers, becoming even greater than PCM for higher vehicle density. This is explained in the next plots, where it is shown that VCM is capable of significantly reducing the amount of data loss.

In general, the amount of handovers is reduced, providing stable connections to vehicles,



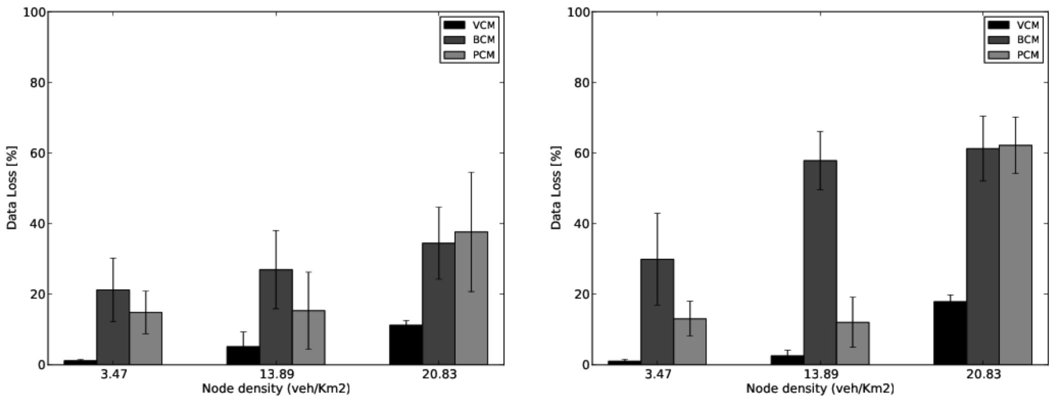
(a) Infrastructure- (b) Infrastructure+

Figure 5.9: Average number of handovers per vehicle

independently of their density, which is explained by the increase in the quality of the mesh network. Furthermore, with the increase of the infrastructure, the number of handovers also increase, which is explained by the capability of VCM by distinguishing infrastructure points according to the available resources.

5.4.3 Data Loss

Figure 5.10 shows the percentage of data loss for all the connection managers, with the variation of the deployed infrastructure and the vehicle density.



(a) Infrastructure- (b) Infrastructure+

Figure 5.10: Data Loss

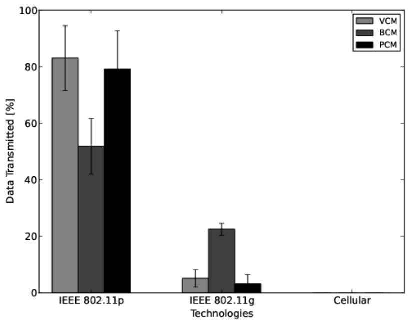
Taking into account the previous conclusion, VCM is capable of significantly reducing the amount of data loss, at the expense of performing more handovers in high density scenarios. In Figure 5.10(a) is possible to observe that VCM outperform the other connection managers in terms of data loss, which is explained by the capability of VCM in select the best candidate according to the characteristics of each vehicle along with the environment.

In an overall view, VCM maintains the data loss below 10 % in every scenario, except when the vehicle density and infrastructure is very high, going to approximately 18 % (Figure 5.10(b)). In this specific case, the other connection managers have nearly 60 % of data loss. This large enhancement provided by VCM is explained by the capability of distinguishing infrastructure points with available resources from those which are overloaded. A large part of this data loss is also explained by the collisions which occurs in the environment medium, due to the high number of simulation nodes.

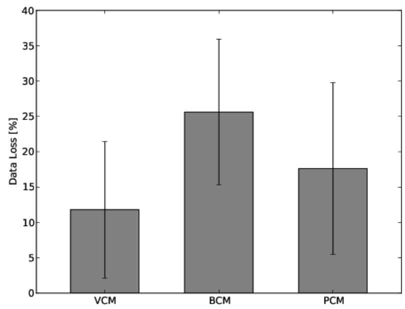
Regarding mesh network, since VCM is capable of analysing how far a mesh node is from the infrastructure, by the number of hops, it is capable to select the gateway which provides a faster way to reach the desired network, with less hops, being this way less prone to disconnections and losing less data.

5.5 Evaluation without Cellular Network

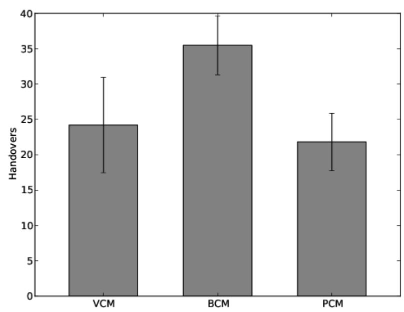
In a different approach, we perform an evalution of our connection manager without the presence of the cellular network. Figure 5.11 shows a comparison between the 3 connection managers in terms of amount data transmitted through each technology, data loss and number of performed handovers.



(a) % Transmitted Data for Technology



(b) % Data Loss



(c) Number Handovers

Figure 5.11: Results - No 3G available

Taking advantage of the already developed Manhattan scenario presented in the previous section, we performed an evaluation with 20 vehicles and the amount of infrastructure deployed shown in Table 5.4; however, the 3G technology was turned off.

Table 5.4: Infrastructure Density

Technology	Infrastructure
IEEE 802.11g	30
IEEE 802.11p	6

In Figure 5.11(a) it is possible to see that BCM was the one among the other connection managers who sent less data through IEEE 802.11p, while VCM had almost the same behavior of the one of PCM. In terms of data loss, VCM outperforms the other connection managers, achieving about 12 % while compared to BCM (27 %) and to PCM (18 %), as shown in Figure 5.11(b). In terms of handovers, Figure 5.11(c), VCM outperforms the BCM which only takes into account the quality of the link, but when compared to the PCM it makes a few more handovers, which is explained with the less data loss achieved.

5.6 Summary

In this chapter we performed the priorities calculation for the AHP, resourting to the GA along with the network simulator NS-3. For that purpose, three scenarios were implemented, taking into account the speed for pre-selection. These scenarios have the purpose of maximizing the amount of real-world situations that may occur, with infrastructure strategically placed. After obtained the priority values, we procceded with their validation using randomly deployed infrastructure but keeping the mobility model and the vehicle density, for each category of speed.

Thereby, in Section 5.4 we proposed a simulation scenario consisting of Manhattan grid, with random traffic, to perform the evaluation of VCM. In this scenario, the mobility models were imported on SUMO, consisting in several vehicles with car-following model and equal turn probabilities, providing a real-world scenario. This evaluation was performed resorting to a comparison to other traditional connection managers, BCM and PCM.

The evaluation takes into account the amount of data sent by each technology, the number of performed handovers and the percentage of data loss. The results show that VCM outperforms the other two connection managers, by accurately determining where to connect based on the available ressources, the signal quality, the expected contact time, among others.

In another approach, we tested the proposed connection manager without the presence of the cellular network. In a comparison to the other connection managers, VCM achieved better again results in terms of data loss, while in terms of handovers, it presented a similar behavior when compared to PCM and better performance when compared to BCM.

Chapter 6

Conclusions and Future Work

6.1 Conclusions

The unique characteristics of VANET networks such as high mobility, dynamic topology and frequent loss of connectivity, turn the network selection scheme into a complex problem, where the decision time is essential for the system performance.

In a crowded wireless environment that we live nowadays, mostly in urban areas, there is a proliferation and overlap of multiple networks and technologies, leading to the network selection mechanism that needs to be capable of taking informed decisions to guarantee connectivity to vehicles in a transparent way for users.

Besides the fact that a large amount of network selection mechanisms have been proposed in the literature, on the one hand, none of these take into account the high mobility of nodes, which is the main feature of VANETs, and on the other hand, they are also not capable of operating in a crowded wireless environment composed by IEEE 802.11p, IEEE 802.11g, cellular network and even IEEE 802.11p Mesh networks. Furthermore, the wireless networks available for a mobile node are in constant change, due to the increase occupancy of the wireless medium, becoming increasly unstable with speed. Thereby, traditional connection managers which only take into account the quality of link or the user preference for the decision process, are not adequate for our problem, due to substantial differences of the environment, specially the high dynamics of VANET.

We concluded that the connection management problem should be re-thought by introducting more dynamic in the decision process, by looking into relevant data that is available in VANET-equipped vehicles, such as the vehicle speed and heading, the position of the infrastructure units along with their availability, and the number of hops to reach the service provider.

Therefore, we proposed the design and implementation of a new connection manager to operate in VANET scenarios - Vanet Connection Manager.

VCM is based on an AHP that combines several candidate networks taking into account preferences, geographic inputs and physical conditions such as the availability, the vehicle speed and heading, and the number of hops to reach the service provider, besides the typical link quality, to determine which of the available networks is more indicated for each user, according to the requirements.

In VANETs, where the high mobility of nodes is the highest challenge presented, we proposed to classify vehicles into three categories, according to speed: **Stopped/Very Slow**,

Moving Slowly and **Moving Fast**. Thereby, the speed was used to pre-select the priority set for the AHP.

For the priorities determination, we proposed the combinations of pairwise comparisons between the criteria involved, according to Saaty's pairwise comparison scale. Furthermore, we proposed to use the comparison scale to rate each alternative according to its properties and enhance the process through simulation, using a Genetic Algorithm, to calculate the optimized priorities for each category of vehicles. Thereby, we created 3 scenarios specifically designed for each category of vehicles, with IEEE 802.11p RSUs, Wi-Fi APs and cellular network, strategically placed to maximize the amount of real-world situations that may occur, for the GA operate and retrieve the optimal priorities for the AHP.

In order to observe the enhancements provided by our connection manager, we used as base two traditional connection managers, to implement BCM and the PCM. BCM is a connection manager which only takes into account the signal quality to select the best network to connect, and PCM has the name suggest it, is a connection manager which takes into account the user preferences combined with the quality of the link.

After achieving the optimal priority values, we performed a validation under scenarios with infrastructure randomly deployed, to ensure that these values were not tied to the specific scenarios for which they were obtained.

According to speed, for **Stopped/Very Slow** vehicles, where nodes move with an average speed of 1 to 2 m/s, VCM achieved less data loss (3 %) when compared to PCM (8 %) and BCM (27 %). In terms of performed handovers, it also achieved better results, less 33 % then PCM and much less then BCM.

For **Moving Slowly** vehicles, where vehicles move with an average speed of 5 m/s, VCM achieved less data loss when compared to the other connection managers, and in terms of number of handovers, it achieved also better results, by performing less handovers.

For **Moving Fast** vehicles, VCM has shown also better results by performing less handovers and having less data loss then PCM and BCM. However, in this case VCM sent around 7 % by cellular network. This is explained by the fact that, in order to achieve stable connections by performing less handovers and reduce at most the data lost, VCM preferred to connect to cellular network even if that costs a little more to users.

We have concluded that VCM had better results in terms of handovers and data loss when compared to PCM and BCM independently of vehicles speed.

To perform the final evaluation of the proposed connection manager in general scenarios, we used SUMO to generate a Manhattan grid with 1.4 km^2 and 400m between roads. Regarding to the scenario, a certain amount of vehicles was introduced to the grid and circulate with equal turn probabilities (25% for each side), using the simulator's car-following model. Vehicles move with top speed of 50 Km/h (urban scenario) and queue at intersections creating real situations where they slow down while approaching the intersections. For the evaluation of the connection manager, we performed experiments for different vehicle and infrastructure densities.

In general, results show that VCM is capable of operating in any urban scenario reducing the data loss and the number of handovers, while compared to the other connection managers. However, for high density scenarios, it is capable of significally reducing the amount of data loss, at expense of performing a little more handovers, which is explained by the capability of distinguishing infrastructure units with available resources from those which are overloaded, and the capability of selecting the gateway with less hops, being this way less prone to disconnections.

We have concluded that VCM outperforms the typical connection managers implemented, being able to balance the load of the network by accurately determining the best candidate to connect, based on the expected contact time, on the available resources of the infrastructure unit and the cost associated for the user, among others. Comparing to the connection managers available in the state of the art, this is the first one that considers the vehicular technology as well as multi-hop communication.

The results presented are quite optimistic: in an overall view, the proposed connection manager improves the network selection problem in VANET scenarios by reducing the number of handovers (more stable connections) and the percentage of data loss (more throughput).

6.2 Future Work

There are several areas that can be pursued for future work.

In terms of prediction, the developed connection manager can be improved. The fact is that VCM only considers the information related to an IEEE 802.11g AP or IEEE 802.11p RSU when the vehicle enters at its range, at the receptions of beacons. Mainly for IEEE 802.11g technology, which has a time-consuming association process and a small range, improving the prediction capability would result in a more effective decision, decreasing the number of handovers and the data loss. As future work, in order to increase the prediction capability of VCM, it is proposed the integration of maps with the infrastructure position, Wi-Fi hotspots and RSUs to predict which network candidates will be available along the path, so that way VCM may take an informed decision, anticipating the connections that will be performed to access the Internet and preparing all the process timely. However, it is needed to take into account that vehicles have limited storage capability. Therefore, it is needed to perform a careful choise related to the information that it is really important, for each interface, ensuring a commitment between the best solution and the complexity of the process. As possible solution, the usage of cloud is in stake, increasing the storage capability of each vehicle and saving all the important information for each one. For the access of the information, the vehicles could relay on cellular infrastructure, but it has associated costs.

Therefore as future work, VCM may also be responsible for the information process, where besides the purpose of choosing the best connection for each vehicle at each time in order to provide connectivity, it may choose the proper connection to gather crutial informations for the main purpose of VCM.

The developed connection manager, as presented in this Dissertation outperforms the other connection managers by presenting better results in term of handovers and data loss while, in simulation environment. However, it is not ready to be installed on vehicles and operate just like in simulation environment. With that purpose, an improvement that needs to be performed is the integration with mobility mechanisms to enable not only the best access, but also seamless access and handovers.

For real-world evaluation, as future work it is expected the integration of VCM in taxis testbed already developed in Porto, to test the implemented mechanism. The integration is expected to be quite simple, since VCM was developed to operate in any scenario, in a dynamic way.

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