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# Mobility Handling and Quality of Service Study of Optical Vehicular Communications

Rami Khoder

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Etude de la mobilité et de la qualité de  
service des communications véhiculaires  
optiques  
*Mobility Handling and Quality of Service Study  
of Optical Vehicular Communications*

**Thèse de doctorat de l'université Paris-Saclay et  
l'université Libanaise**

École doctorale n° 580, Sciences et Technologies de l'Information et de  
la Communication (STIC)

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**Thèse présentée et soutenue à Paris-Saclay,  
le 06/09/2021, par**

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**Titre:** Etude de la mobilité et de la qualité de service des communications véhiculaires optiques

**Mots clés:** Speed Platoon Splitting (SPS), Radio Fréquence (RF), Communication par lumière visible, Qualité de Service (QoS), Handover Vertical (VHO)

**Résumé:** La dernière décennie a connu l'augmentation des accidents de la route et la circulation a augmenté rapidement avec la croissance du secteur automobile et la démocratisation des voitures. Les chercheurs ont démontré que le nombre élevé d'accidents sur la route est principalement dû à l'incapacité et à la lenteur des conducteurs à prendre la bonne décision. Les stratégies de formation des véhicules et les systèmes de communication entre véhicules sont considérés comme des solutions à ces problèmes.

La communication entre véhicules, connue sous le nom de "vehicule-to-everything" (V2X), qui comprend les communications de véhicule à véhicule (V2V) et de véhicule à infrastructure (V2I), permet aux véhicules d'échanger des messages de sécurité routière et de gestion du trafic avec une faible latence. La formation de platoon est une option interactive qui peut améliorer la communication V2X et assurer une bonne sécurité. Le platoon de véhicules est défini comme un groupe de véhicules se suivant les uns les autres, se déplaçant en ligne droite avec un espace inter-véhicules très court. Plusieurs stratégies de formation de pelotons de véhicules ont été définies afin d'en gérer la durée de vie ainsi que la stabilité. Cependant, aucune de ces stratégies n'a pris en compte les contraintes de circulation et de vitesse. Notre travail de recherche comporte trois objectifs. Dans la première phase, nous avons proposé un nouvel algorithme de formation de peloton appelé Speed Platoon Splitting (SPS) où les véhicules sont regroupés en fonction de leur destination (le véhicule de tête a la destination la plus lointaine et le dernier véhicule a la destination la plus proche). SPS vise à réduire la congestion en utilisant un pool de tickets et classe les pelotons en fonction de leur vitesse sur deux voies différentes. L'analyse des performances montre que le SPS assure la stabilité des pelotons et réduit la circulation sur l'autoroute. Les communications V2X peuvent être réalisées via

les technologies de radio fréquence (RF), en particulier la standard 802.11p. Cependant, en raison de la progression accélérée du nombre de dispositifs, cette technologie souffre de plusieurs problèmes tels que la latence élevée et la congestion des canaux. Une solution de communication alternative est fournie par la communication par lumière visible (VLC). Le VLC est une technique de transmission de données sans fil qui utilise la lumière visible. La VLC réduit la complexité et le coût, permet un positionnement de haute précision et augmente l'évolutivité et la sécurité du réseau.

Le deuxième objectif de cette thèse se focalise sur les performances du VLC dans la communication V2V entre les membres du peloton. Nous avons considéré deux modèles mathématiques validés par des simulations pour deux scénarios différents (nous avons pris une file d'attente M/M/1 et une file d'attente M/GI/1 pour le premier et le second scénario respectivement). Les résultats montrent une étude très détaillée de la performance du VLC en présence de véhicules perturbateurs où nous avons dérivé le paramètre de qualité de service (QoS). La technologie VLC est considérée comme une technique efficace pour les pelotons, qui sont affectés par des véhicules gênants.

Le troisième objectif de la thèse se concentre sur la proposition d'un mécanisme de handover vertical entre les technologies VLC et RF. Cet objectif est composé de deux parties, la première est la décision de faire un handover vertical (VHO) en utilisant la valeur seuil ou la technique d'apprentissage automatique. La deuxième partie consiste à choisir la technologie appropriée après le VHO en utilisant la fonction d'utilité ou le jeu coopératif.

Tout au long de la thèse, l'évaluation des performances du VLC est basée sur la modélisation mathématique. Par ailleurs, la simulation est réalisée pour valider cette modélisation mathématique.

**Title:** Mobility Handling and Quality of Service Study of Optical Vehicular Communications

**Keywords:** Speed Platoon Splitting (SPS), Radio Frequency (RF), Visible Light Communication (VLC), Quality of Service (QoS), Vertical Handover (VHO)

**Abstract:** The thesis topic is a part of the global interest in wireless vehicular networks. Over the past decade, the number of road accidents has increased quickly with the growth of the automotive sector. Statistics have demonstrated that the high number of accidents on the road is primarily due to the high traffic density and the lack of information about other drivers' decisions. Recent studies have shown the importance of vehicular communications, which allow the exchange of real-time traffic safety information between vehicles and thus contribute to accidents avoidance.

Through vehicular communication, known as vehicle-to-everything (V2X), which includes vehicle-to-vehicle (V2V) and vehicle-to-infrastructure, vehicles can exchange road safety and traffic management messages with low latency. Platoon formation is considered an interactive option that can improve V2X communication and ensure more safety. The vehicle platoon is defined as a group of vehicles following each other, moving in a straight line with a very short inter-vehicle space. Several vehicle platoon formation strategies have been defined in order to manage the platoon's lifetime and stability. However, none of these strategies has taken into account traffic congestion and speed constraints.

The first objective of our work is to propose a new platoon formation algorithm called speed platoon splitting (SPS) where vehicles are grouped according to their destination (the leading vehicle has the farthest destination and the latest vehicle has the nearest destination). The main purpose of SPS is to target alleviating congestion by using a ticket pool and classify platoons according to their velocity in two different lanes. Performance analysis shows that SPS provides platoon stability and reduces highway congestion.

V2X communications can be achieved via radio frequency (RF) technologies, especially the 802.11p standard. However, due to the accelerated growth in the number of devices, this technology suffers from several problems such as high latency and channel congestion. An alternative communication solution is provided by visible light communication (VLC). VLC is the usage of visible light as a wireless data transmission technique. VLC reduces complexity and cost, enables high precision positioning and increases network scalability and security.

The second objective of this thesis tackles the performance of VLC in V2V among the platoon members. For this purpose, we considered two mathematical models validated by simulations for two different scenarios (we have taken an M/M/1 and an M/GI/1 queues for the first and the second scenarios respectively). The performance evaluations present a detailed study of the VLC in the presence of disruptive vehicles and they are used to derive computations of the Quality of Service parameters. The main conclusion drawn is that VLC technology is considered an efficient technique but it is affected by disruptive vehicles.

The third objective of the thesis focuses on proposing a mechanism for vertical handover (VHO) between VLC and RF technologies. This objective is composed of two parts, the first one is based on the threshold value to make a vertical handover decision or by using machine learning techniques. The second part is to choose the appropriate technology after VHO using the utility function or the cooperative game.

Throughout the thesis, the performance evaluation of the VLC is based on mathematical modelling. Moreover, the simulation is performed to validate this mathematical modelling.

# Acronyms

ACC	Adaptive Cruise Control
ALM	Aggregate Local Mobility
ADC	Analogue-to-Digital Converter
AP	Application Unit
AI	Artificial Intelligence
ANNs	Artificial Neural Networks
BER	Bit Error Rate
CSMA/CA	Carrier-Side Multiple Access with Collision Avoidance
CPA	Closest Position to Average
CH	Cluster Heads
ComS	Communities Services applications
CACC	Cooperative Adaptive Cruise Control
CA	Cooperative Awareness
CDA	Cooperative Driver Assistance
CoNa	Cooperative Navigation
CSM	Cooperative Speed Management
DCA	Distributed Clustering Algorithm
DL	Deep Learning
DG	Destination Group
DMAC	Distributed Mobility-Adaptive Clustering
DSRC	Dedicated Short-Range Communications
DYG	Dynamic Grouping
DGPS	Dynamic Grouping and Platoon Splitting
ETSI	European Telecommunications Standards Institute
EU	European Union

FCC	Federal Communications Commission
FOV	Field Of View
GPS	Global Positioning System
GRAA	Grey Relationship Analysis Algorithm
GRC	Grey Relationship Coefficient
HO	Handover
HHO	Horizontal Handover
IR	Infra-Red
ITS	Intelligent transportation system
KNN	K-Nearest Neighbors
LiFi	Light Fidelity
LED	Light-Emitting Diode
LOS	Line Of Sight
LAN	Local Area Network
LBS	Location-Based Services
ML	Machine Learning
MAC	Media Access Control
MADM	Multiple Attribute Decision Making
MADMA	Multiple Attributes Decision-Making based Algorithm
NS2	Network Simulators
Omnet	Objective Modular Network Testbed
OBU	On-Board Unit
OFDM	Orthogonal Frequency Division Multiplexing

P2P	Peer to peer
PD	Photo-Detection
PV	Photovoltaic
POI	Point Of Interest
PVHO	Prediction vertical handover
QoS	Quality of Service
RATs	Radio Access Technologies
RF	Radio Frequency
RA	Random Assignment
RTVR	Real-Time Video Relay
RSS	Received Signal Strength
RHCW	Road Hazard and Collision Warning
RSU	Road Side Unit
SA	Service Announcements
SINR	Signal to Interference and Noise Ratio
SNR	Signal-to-Noise Ratio
SAW	Simple Additive Weighting
SVM	Support Vector Machine
SUMO	Simulator for Urban Mobility
USDOT	United States Department of Transportation
VSC	Safety Communication Project
V2I	Vehicle to Infrastructure
VHRP	Vehicle-Heading Based Routing Protocol
V2X	Vehicle-to-Everything
V2N	Vehicle-to-network
V2P	Vehicle-to-Pedestrian



V2V Vehicle-to-Vehicle  
VSS Vehicular Sharing Services  
VHO Vertical Handover  
VST1 Virtual Service Time  
VLC Visible Light Communications

WUF Weighted Utility Function  
WCDMA Wideband Code Division Multiple Access  
WLAN Wireless local area network  
WSN Wireless sensor networks  
WWAN Wireless wide area network  
WDP Wrong Decision Probability



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# 1. Chapter 1: Introduction

## 1.1 Thesis Concerns

The great development and the fast evolution of the wireless technologies field have made it possible to rethink the driving model by introducing the notion of cooperation between vehicles. The success of the introduction of wireless technology in the vehicle sector is strongly correlated with the implementation of road active security services with high added value for the driver.

In fact, the deployment of a wireless network between vehicles makes it possible to transmit crucial warning information for the provisioning of active preventive safety. This information assists the driver and facilitates the decision-making process which provides the driver with an enhanced vision. Nevertheless, the regular distribution of alert messages to all vehicles could overload the network. Therefore, the determination of the receivers of road safety information, within a convoy, as well as the frequency of transmission is a necessity.

IEEE 802.11 p and LTE-V are two main wireless standards advocated for carrying vehicular applications. Nowadays, the performance of the IEEE 802.11p protocol is very well known. Several studies have investigated network performance [1]–[6], with similar conclusions: the protocol has natively an interesting property of spatial resource reuse, but it presents important problems concerning scaling. The problem of congestion control in IEEE 802.11p networks is a current topic in the field [7], [8].

On the other hand, VANETs ad hoc networks are characterized by the rapid mobility of the vehicles. In addition, vehicles suffer from discontinuous connectivity and network partitioning. It should be noted that network performance falls with vehicle density. These problems are closely linked to the network scale transition property which is one of the objectives of hierarchical networks.

In this thesis, we have identified the need to implement a set of solutions that could compensate for the performance degradation of RF technologies at heavy traffic loads. In fact, the additional need for higher data rates improved security, and increased energy efficiency has geared attention towards the optical spectrum which offers abundant unregulated bandwidth, low interference, and cost-effective communication as compared to radio frequency and 802.11p bands. This has spurred the investigation in visible light communications (VLC) as a potential candidate for complementing and offloading RF communication systems.

In order to address the scaling issue, we focus on VLC platooning that arranges the network into groups of nodes. Thus, vehicles are grouped in a convoy in a hierarchical architecture, with groups of vehicles at the first level and group leaders at the second level. Thus each convoy, or platoon of vehicles, will be piloted by the head of the convoy; the heads of the different convoys will be responsible for spreading the messages. This would reduce the consumption of radio bandwidth.

The introduction of convoy drivers brings up the issue of platoon formation. Indeed, given the high mobility of the vehicles, the platoon should be constituted while taking into account the vehicle's destination and reducing the convoy splitting problem.

In this context, optical direct communication between vehicles makes a significant contribution to improving the efficiency of the vehicle platoon. At this moment, the performance of VLC technology in vehicle networks is very little studied in the literature and deserves to be evaluated.

The thesis consists of examining the benefits of implementing a direct optical communication medium based on white light generated by LEDs between vehicles arranged in a platoon. The main objective is to evaluate the performance of the LIFI network for convoy applications. Moreover, we are particularly interested in the complementary nature of the RF technology and VLC while emphasizing the quality of service and the hierarchical structure within a platoon.

## 1.2 Contributions

This thesis consists of evaluating the performance of direct optical communication based on visible light generated by diodes LED between vehicles organized in convoys. In case of QoS degradation, we apply a vertical handover (VHO) from VLC to a suitable RF technology.

Our thesis objectives presented in figure 1.1 are three-fold:

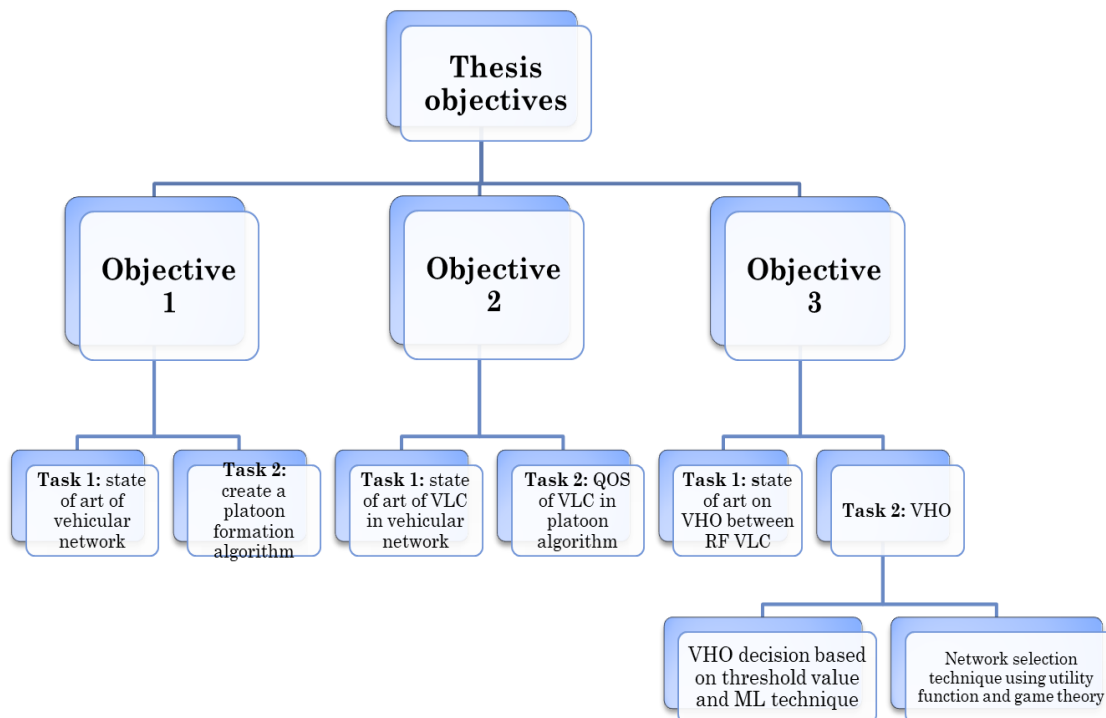


Figure 1.1: Thesis objectives

### **Objective 1:**

The platoon formation algorithm is in fact the essential to tackle convoy formation in order to reduce platoon splitting.

- Task 1: We started with a state of the art on algorithms of vehicles clustering. This survey has inspired us on VLC platoon formation
- Task 2: We proposed an algorithm of platoon formation that aims at reducing the time required to associate the platoon leader and increasing the platoon life-time.

### **Objective 2:**

The performance study of VLC technology in the context of a convoy is communicating vehicles with the presence of interfering vehicles.

- Task 1: We elaborated a bibliographic study of VLC technology used in vehicular network.
- Task 2: We evaluated the efficiency and quality of service of the VLC in the presence of interfering vehicles. This was achieved with a M/GI/1 multi-class mathematical modelling.

### **Objective 3:**

The complementarity study of the current access methods is RF technology (802.11p and LTE-V) and VLC.

- Task 1: We elaborated a state of art on the vertical handover between the RF and the VLC technology.
- Task 2:
  - We proposed a VHO decision, based on machine learning strategy for two different scenarios (night and sunlight case). We inject vehicular data into different machine learning classification algorithms; The objective is to make the decision on the most appropriate wireless technology.
  - We proposed a network selection technique based on a utility function coupled with a cooperative game theory. The cooperative game is proposed to prevent network overloading and reduce unnecessary handover transitions. The primary objective of the cooperative game is to determine the strategies that optimize the utility function for each network where the technology that provides a high selection ratio is the most uncongested network.

## **1.3 Work Context**

This work is conducted conjointly between the Lebanese University(LU)- Centre Azm, Tripoli, Lebanon and Li-Parad Laboratory, Versailles Saint Quentin En Yvelines University (UVSQ), France. The thesis duration is organized as follows: 8 months in LU and 4 months in UVSQ for three years. The research studies during the fourth year were entirely achieved in LU.

## 1.4 List of Publications

In the following, we list the works published during the Ph.D research studies:

### Published Works

**R.Khoder**, R.Naja, S.Tohme. SPS algorithm in Vehicular Networks. In Proc. of the Junior Conference on Wireless and Optical Communications, February 2019, Paris, France.

**R.Khoder**, R.Naja, S.Tohme. Performance Evaluation of Speed Platoon Splitting Algorithm. In Vehicular Ad-hoc Networks for Smart Cities IWVSC'2019, Paris, France. In Advances in Intelligent Systems and Computing, vol 1144. Springer, Singapore. [https://doi.org/10.1007/978-981-15-3750-9\\_3](https://doi.org/10.1007/978-981-15-3750-9_3).

**R.Khoder**, R.Naja, S.Tohme. Impact of Interference on Visible Light Communication Performance in a Vehicular Platoon. In Proc. IEEE International Wireless Communications and Mobile Computing Conference IWCMC, May 2020, Limassol, Cyprus, pp. 1935-1939, doi: 10.1109/IWCMC48107.2020.9148127.

**R.Khoder**, R.Naja, N.Mouawad, S.Tohme. Vertical Handover Network Selection Architecture for VLC Vehicular Platoon Driving Assistance. In Proc. IEEE International Symposium on Personal, Indoor and Mobile Radio Communications PIMRC, June 2020, London, United Kingdom, pp. 1-6, doi: 10.1109/PIMRC48278.2020.9217118.

N.Mouawad, **R.Khoder**, R.Naja, S.Tohme. Vertical Group Handover Congestion Game for a Vehicular Platoon in VLC Networks. Submitted to journal of Annals of Telecommunications.

## 1.5 Thesis structure

This thesis is structured as follows. In chapter 2, we review the main key concepts of Intelligent Transport Systems. Moreover, we focus on the integration of the RF and VLC technologies in vehicular networks. In chapter 3, we present Vehicle Formation Strategies and we shed the light on vehicle platooning. These two chapters are conducted during the first year. Chapter 4 is dedicated to Vertical mobility.

Chapter 5 introduces our first contribution to the Visible Speed Platoon Splitting SPS Algorithm. Our second contribution, related to VLC performance evaluation, is described in chapter 6. The Vertical handover between VLC and RF technology is presented in chapter 7. At the first stage, we define the vertical handover decision. At the second stage, the techniques used for vertical HO are presented. Chapter 8 concludes this thesis work and presents our future research perspectives.

## 2. Chapter 2: Intelligent Transportation Systems

### 2.1 Introduction

The U.S. surface transportation system consists of 3.9 million miles of roads and 503 public transportation systems, which handle 4 trillion passenger miles and 3 trillion tons of freight per year [9]. In 2006, the US Department of Transportation reported that America faces a loss of \$200 billion a year due to congestion and slow freight deliveries. Besides, consumers lose 3.7 billion hours and 2.3 billion gallons of fuel in road congestion.

There is a rapid increase in demands on the transportation system, with a predicted 25% increase in highway miles covered over the next ten years [10]. To avoid traffic congestion, there are two options, the first one is to increase highway capacity by raising the number of lanes. The second option consists of enhancing the efficiency of the existing transport system and improving the use of public transport systems. This option aims to reduce the number of kilometres covered, and focus on investing in Intelligent Transport Systems (ITS) infrastructure.

About 1.3 million people died in road accidents worldwide, more than 20 million were injured. Around half of the deaths are among road users such as pedestrians, cyclists and motorcyclists [11]. Road traffic accidents are the primary reason for the death of young generations worldwide. The majority of these accidents occur in countries where road safety awareness is relatively low.

The level of passenger comfort is a major parameter for evaluating the user experience in any type of transportation, especially in autonomous vehicles. One of the key elements that affect user acceptance of autonomous vehicles is the comfort level of the passenger in a situation of "control and lack of authority".

This chapter introduces the ITS and the different types of technologies used. We begin first of all with section 2.2, which provides an overview of the ITS components, applications and communication technologies. Then, we shed the light on the RF and the VLC technologies used in ITS where we explore the research projects, the adopted scenarios, applications, the challenges and the issues faced by each technology in sections 2.3 and 2.4. Finally, we conclude the chapter in section 2.5.

## 2.2 Intelligent Transportation Systems

Over the past decade, Intelligent Transport Systems have gained significant attention from the research community because of the effective solutions that can change the driver's lifestyle and ensure their safety. An integrated approach to travel management, travel plans, traffic demand, emergency management, route pricing, parking and transport uses is required from ITS systems. ITS apply information, data processing, communication, sensor technologies to vehicles and transport infrastructure.

ITS [12] enable the exchange of data between vehicles or between vehicles-infrastructure. The main feature of ITS is the ability to share specific information between vehicles and support a wide range of applications. To enable vehicle-to-vehicle communications, ITS smart vehicles will be designed with network interfaces, sensors, in-vehicle computing capabilities and video cameras. This enables infrastructure elements to interact with vehicles and infrastructure.

Therefore, ITS [13] can increase the effectiveness and environmental performance, improve traffic management, enhance active road safety and provide informative data.

### 2.2.1 Vehicular communication types

The level of vehicle safety is related to the communication between vehicles and all elements of the ITS. For this reason, Vehicle-to-Everything (V2X) communication is introduced [12].

Vehicles can support several V2X services simultaneously using different modes of communication. More specifically, V2X consists of four communication modes (figure 2.1): Vehicle-to-Vehicle (V2V), Vehicle to Infrastructure (V2I), Vehicle-to-network (V2N) and Vehicle-to-Pedestrian (V2P).

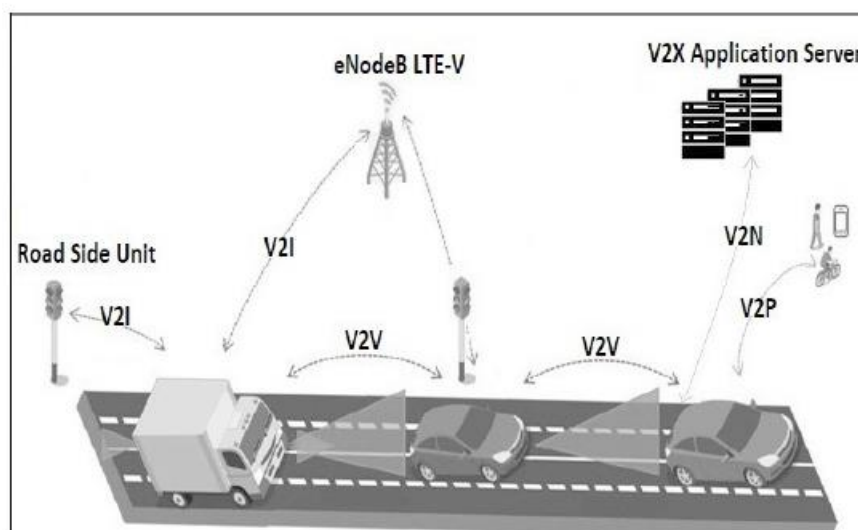


Figure 2.1: V2X communication modes [14]

### **2.2.1.1 Vehicle-to-Vehicle (V2V)**

A V2V network is a network that is composed only of intelligent vehicles without infrastructure, where wireless communication devices are installed in the vehicle. Vehicles are usually moving with close-range communication systems and can share information with other vehicles in their coverage, which results in the development of vehicle ad-hoc wireless networks.

V2V communications are adapted for both real-time active safety and emergency knowledge, which must therefore be rapid, secure. V2V enables safety-critical applications such as electronic emergency brake lights, cooperative collision warning, blind-spot warning and lane change support. Besides, there are various non-safety related applications such as downloading, surfing the Internet, and many more [15].

V2V applications require that vehicles be close to each other to exchange V2V information. This information includes speed, direction, and braking status. Vehicles may communicate directly with each other or indirectly via intermediate vehicles [16], [17].

### **2.2.1.2 Vehicle-to-Infrastructure (V2I)**

In the preceding section, we presented V2V networks without infrastructure. This deployment has several advantages but induces two major drawbacks. V2V communications are not reliable, particularly when the number of vehicles is limited.

Therefore, it is usually recommended to complement V2V networks with infrastructure vehicle networks. V2I communications allow the transfer of messages between vehicles and infrastructure. V2I handles road safety messages with safety-related information such as road accidents. Moreover, V2I networks deliver broadband reliable communication services, provide online resources and access to local non-vehicle-based services. The V2I infrastructure offers two kinds of Access: function-specific ports and communication ports.

Vehicles are communicating for specific tasks. Examples of such vehicles are wireless traffic controllers that enable signal priority (priority for emergency vehicles). Communication ports, for example, access points and base stations, are considered another type of connection that allows users to access the network.

### **2.2.1.3 Vehicle-to-Network (V2N)**

V2N [18] enables both broadcast and unicast communications to take place between vehicles. V2N systems are used to connect vehicles to the wireless infrastructure where vehicles can take advantage of in-car services such as traffic updates and media streaming.

### **2.2.1.4 Vehicle-to-Pedestrian (V2P)**

V2P (Vehicle-to-Pedestrian) [19] involves direct communications between a vehicle and a pedestrian or multiple pedestrians within close range. It provides warning messages to the

pedestrian (using their mobile phones or other radio equipment) in case a vehicle is approaching, and warnings of vulnerable road users to vehicles.

## 2.2.2 Vehicular Network Components

V2X communication consists of three elements [20] as we can see in figure 2.2: Road Side Unit (RSU), On-Board Unit (OBU) and Application Unit (AU).

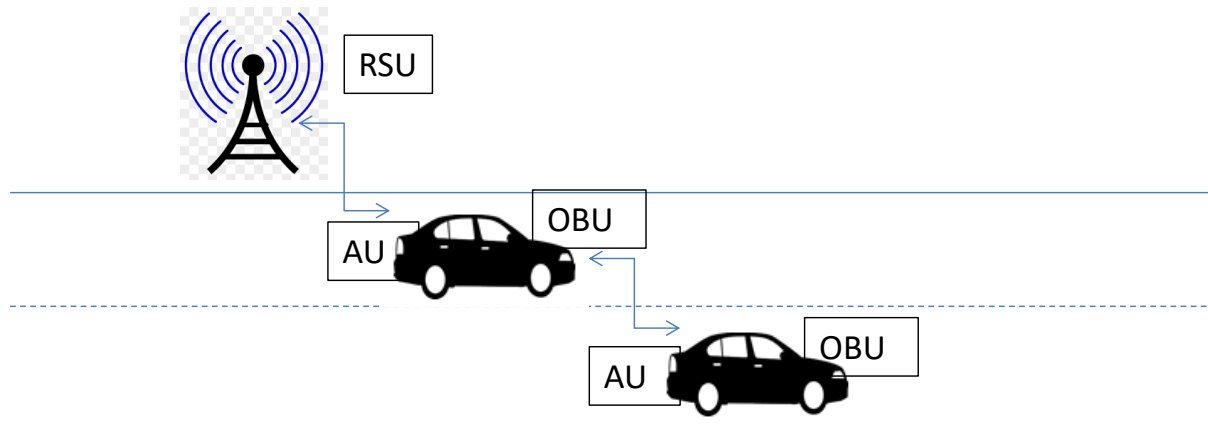


Figure 2.2: Vehicle networks components

### 2.2.2.1 Road Side Unit

RSU is a wireless access device in the area of a vehicle that runs only when the vehicle is stationary and allows the data to be shared between the OBUs. It is usually installed along with the road transport network or in specific locations such as crossroads. The major role of an RSU is to carry out safety applications such as accident warning or work area, using V2I communications.

### 2.2.2.2 On-Board Unit (OBU)

OBU is a facility mounted on-board of an intelligent vehicle for communication and used for exchanging information with RSUs or with other OBUs. An OBU is a wireless mobile that allows the exchange of information with RSUs and other OBUs which can perform when it is in movement.

### 2.2.2.3 Application Unit

The AU is equipment installed in the vehicle. It uses the applications provided by the provider using the communication capabilities of the OBU.

## 2.2.3 ITS applications

In the literature, a large number of studies have been carried out on the classification of security applications [21]–[23]. We have therefore found that vehicle applications are categorized into three major groups: safety, traffic management and comfort, as shown in Figure 2.3.



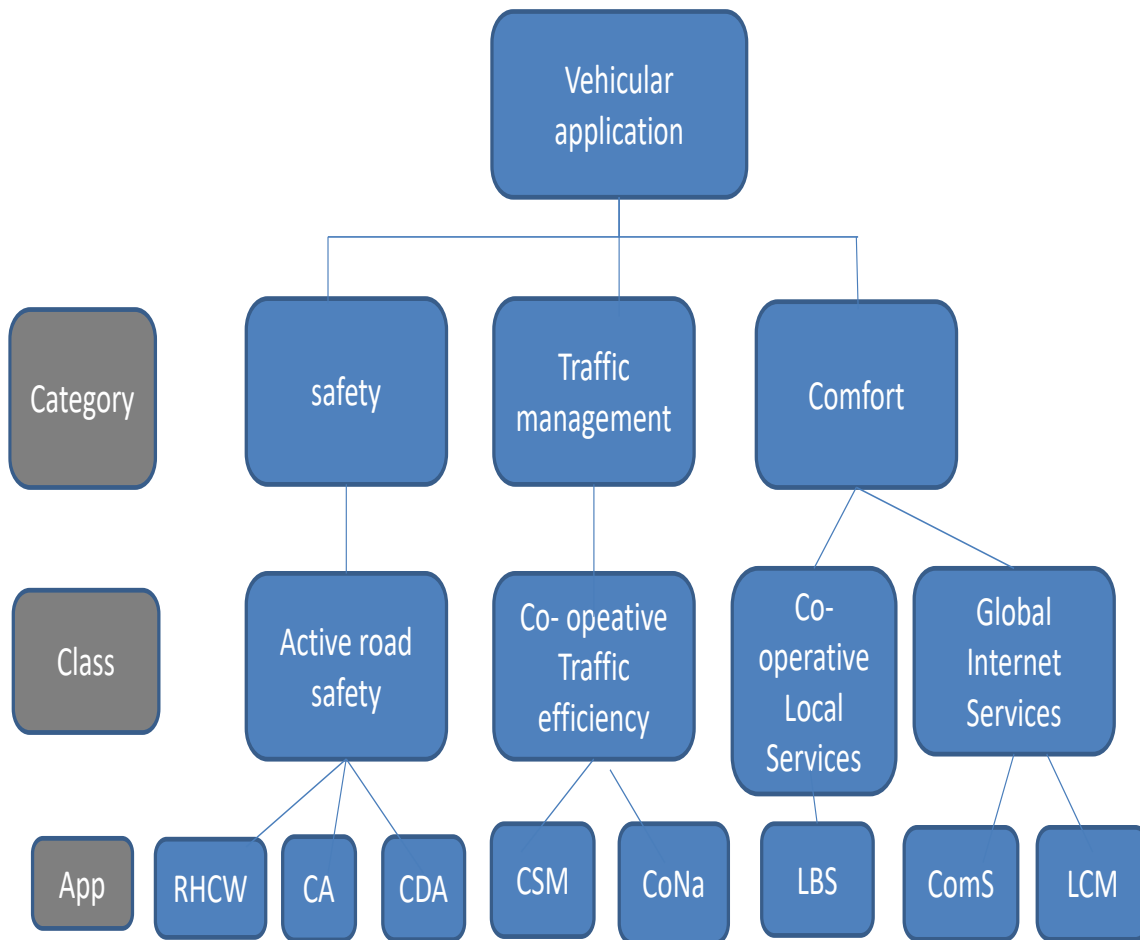


Figure 2.3: Vehicle application classification [22]

### 2.2.3.1 Safety category

Safety applications [18] have gained significant attention since they aim at preventing road accidents. The safety category is associated with the active road safety category, which targets the provision of awareness, assistance and warning services to drivers through Cooperative Awareness (CA), Cooperative Driver Assistance (CDA) and Road Hazard and Collision Warning (RHCW) applications (Fig. 2.3).

In fact, under normal driving conditions, the driver needs to obtain information about the surrounding dangers. This information is provided by the active road safety application which notifies the driver of dangerous road conditions and accidents. In other terms, active road safety applications are responsible for warnings, awareness and assistance.

RHCW is based on Road risk management and collision alert applications that offer information on impending collisions due to unsafe road conditions, obstacles and irregular drivers. The RHCW can warn the driver, preload the brakes pump up the seats for extra support, retract seatbelts to eliminate unnecessary slack and then brake automatically (partial or full brakes) to avoid a collision [24].

Cooperative Awareness applications assist drivers in situation awareness and give information about the surrounding vehicle in their coverage area using both internal and external resources.

The main idea of cooperative driving systems is the reduction of emergency brake that may cause a collision between vehicles, by ensuring a safe distance between cars. This application takes into consideration the environment, in addition to the movement of the leading vehicles. In other words, if the distance between vehicles changes, cooperative driving systems have to react properly by accelerating, decelerating or braking.

### **2.2.3.2 Traffic Management category**

The Traffic Management category is associated with the Cooperative Traffic Efficiency category (Fig.2.3). Congestion occurs when vehicle traffic exceeds the capacity of the highway. Several applications are studied in different projects [24]–[28] to reduce congestion. One of the policies is the Cooperative Traffic Efficiency application which provides a real-time response to congestion and introduces two applications: Cooperative Speed Management (CSM) and Cooperative Navigation (CoNa).

CSM consists of two services. The first one is the speed limit warning, the current regulation speed and several speed recommendations. The second is the Traffic Light Optimal Speed Advisory, which is responsible for optimal speed advice on traffic lights.

CoNa application [29] is considered a location indicator based on the geographical location of the vehicles, which helps drivers to locate optimal routes, hotels, restaurants, or other points of interest. The CoNa messages will include local traffic information, some traffic information and recommended routes.

### **2.2.3.3 Comfort category**

The last category of target passengers is comfort. The comfort category includes cooperative local services, the global Internet services class and the Life Cycle Management (LCM). This application has the lowest priority compared to the safety application which must be provided to drivers on time without any delay.

The Cooperative local services class provides Location-Based Services (LBS) application that provide the Point Of Interest (POI), Service Announcements (SA), Real-Time Video Relay (RTVR), Vehicular Sharing Services. The Communities Services applications (ComS) offer Insurance and Financial Services, Fleet Management services and Monitoring and Tracking. ITS station (LCM) applications contract Vehicle, RSU Data Calibration Remote and Vehicle personalization.

## **2.2.4 Communication technologies**

Several car manufacturing companies have already been testing the available wireless technologies to provide safety applications. Some technology companies such as Google, Microsoft

and Apple compete against each other to offer the most appropriate technology for connected vehicle platforms. The main radio access technologies (RATs) such as ZigBee, Bluetooth, DSRC/ 802.11p, LTE-V and VLC are the potential candidates for V2V communication. Since in our thesis we used the IEEE 802.11p, LTE-V and VLC we have introduced these technologies in the next subsections.

### 2.2.4.1 DSRC/ IEEE 802.11p

The primary radio access technology enabling V2X communication is DSRC known by the 802.11p that is defined by the U.S. Federal Communications Commission (FCC). The DSRC specifies 75 MHz of spectrum, in the 5.9 GHz region, where the spectrum is divided into 10 MHz channels. On the other hand, ETSI defined ITS-G5, which specifies protocols and requirements that constitute the European version of this technology. ITS-G5 is based on DSRC, with some architectural modifications. The main motivation for DSRC deployment is to ensure road safety and traffic efficiency.

IEEE 802.11p is derived from the former IEEE 802.11a standard and used to support the requirement of V2X communication. IEEE 802.11p defines physical transmission and media access control (MAC) as shown in Figure 2.4. It uses Orthogonal Frequency Division Multiplexing (OFDM) and applies Carrier-Side Multiple Access with Collision Avoidance (CSMA/CA), defined by listening to the channel before starting its transmission. When the channel is busy, the device postpones its transmission by a random amount of time, defined by the contention window.

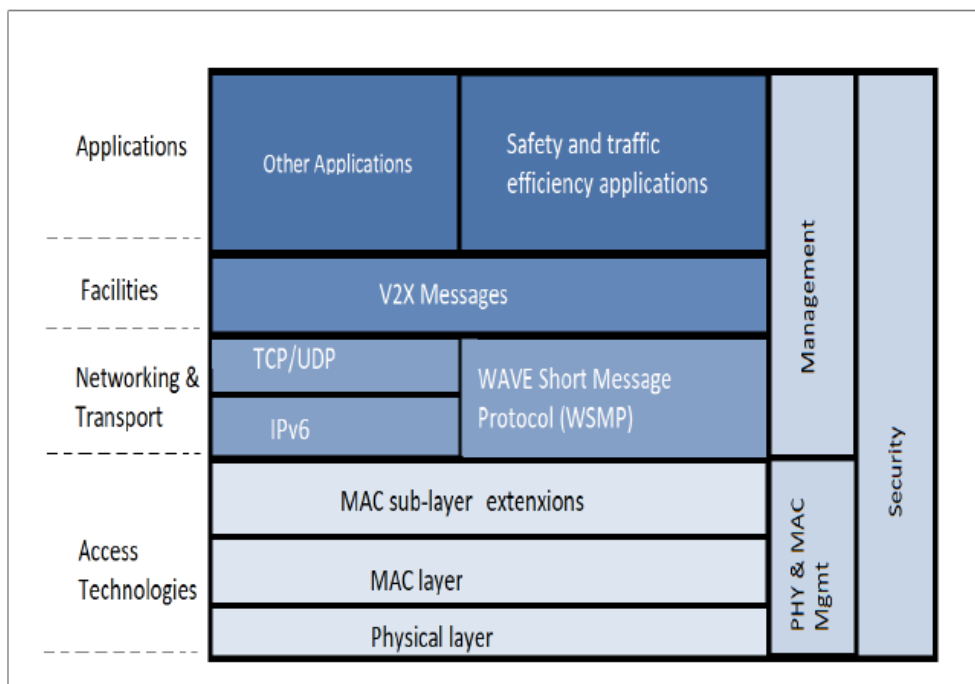


Figure 2.4: Protocol stack and related core standard for DSRC [30], [31]

Like DSRC, ITS-G5 (figure 2.5) operates in the 5.9 GHz band, whereas the European spectrum allocation is sub-divided into part A to D. Mainly, ITS-G5A with 30 MHz is the primary frequency band that is dedicated for safety and traffic efficiency applications and ITS-G5B has 20 MHz for non-safety application. At the PHY layer, ITS-G5 applies OFDM. At the MAC layer, ITS-G5 also employs CSMA/CA.

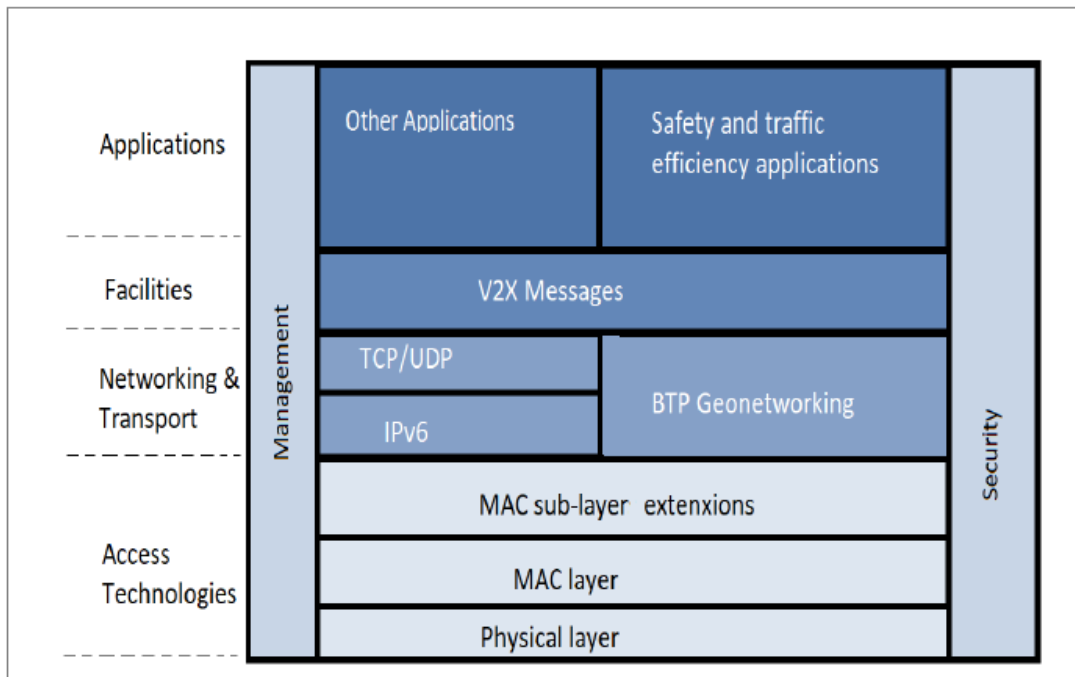


Figure 2.5: Protocol stack and related core standards for ITS in Europe [30]

To make sure that all vehicles with different geographical areas can receive information, DSRC protocol is deployed in different geographical coordination for addressing and forwarding [31].

#### 2.2.4.1 LTE-V

Compared to IEEE 802.11p, LTE-V adds a redundant transmission which can increase the reliability. LTE-V standard includes two radio interfaces as we can see in figure 2.6 that support V2I communication (uplink and downlink). LTE-V was first introduced in version 12 [32] for public safety and has two modes of operation: Mode 1 and Mode 2. Both modes are introduced with the same purpose of improving the lifetime of the battery in mobile devices. V2X communications required a low latency for the connected vehicles.

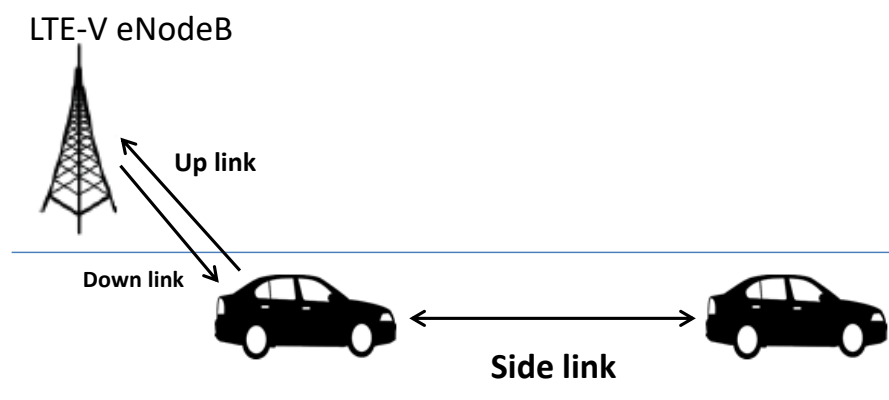


Figure 2.6: LTE-V radio interfaces

In September 2016, the first version of release 14 3GPP is published that includes the V2X communications support [31]. This standard is commonly referred to LTE-V, LTE-V2X, or cellular V2X.

Starting from version 14, LTE-V adds extra features to provide V2X communication. The functionalities are improved at both levels: radio network level as well as at the core network level. Release 14 introduces two new communication modes for V2V communications, mode 3 and 4 are used to select radio resources, while mode 4 are only used for safety applications that cannot depend on the disponibility of cellular coverage.

LTE-V2X Services In the following, we cover use cases and potential requirements for LTE-V technology. These use cases, proposed in 3GPP release 14 [24], are listed as follows:

- **Forward collision warning:** This application is designed to notify drivers of a collision.
- **Control LossWarning:** This use case allows a vehicle to diffuse to surrounding vehicles the loos of control.
- **V2V use case for emergency vehicle warning:** This use case allows each vehicle to collect location, speed and information from a neighbouring emergency vehicle ( ambulance ).
- **V2V emergency stop use case:** This is used in the event of an accidental stop to activate a more secure driving response for other vehicles.
- **Cooperative adaptive cruise control:** This use case provides information regarding a vehicle with V2V capability that will join or leave the group of vehicles
- **Road safety services:** In this use case, V2X messages are transmitted between two User Equipment (UE) that support the V2I services via an RSU.
- **Automated parking system:** This usage case includes a real-time database that contains vehicle information on the parking place's availability.
- **Curve speed warning:** This application warns the driver to handle the curve at a suitable speed.

## 2.3 RF technologies for ITS

In recent years, the ITS has attracted a lot of interest in overcoming a variety of traffic problems [33]. The primary objective of the LTE-V and IEEE 802.11p [34] standard for short/medium distance for vehicular communications is to provide road safety and enhance road traffic efficiency. It is noteworthy that these technologies have been designed to achieve a low latency over a significant communication range.

### 2.3.1 Research projects

Different projects and applications tackled the adoption of RF technologies tailored to ITS. These projects focus on V2X communication and especially communication between vehicles and between vehicles-infrastructure

One of the projects related to the safety traffic is provided by the united states department of transportation (USDOT), which carried out more than eight vehicles under the title of Vehicle Safety Communication Project (VSC) [35]. As a result of this collaboration, potential new secure and non-secure applications were introduced as well as the communication needs of each application were determined. More importantly, these applications were classified for the first time and

evaluated according to their prospective future for short, medium, or long-term needs. Listed applications included curve speed warning, lane change, traffic light warning, crash warning, turning assistance and stop sign moving support. The VSC project has studied different wireless communication technologies such as DSRC, 4G cellular system, Bluetooth, Zigbee and radar systems. USDOT has introduced a subsequent project called Vehicle Safety Communication Application (VSC-A) that aims to improve and evaluate the existing vehicular safety systems [36].

The eSafety, PReVENT, COOPERS, COMeSafety, PRE-DRIVE C2X and CVIS [37] projects have the same objective of studying ITS applications. These projects have been initiated and carried out by the European Union (EU) to develop ITS solutions, but based on different types of applications and different safety requirements. These projects [38] were designed for V2I communication to enhance traffic systems. However, SAFESPOT focuses on V2V communication to achieve safety improvements by providing a Cooperative mode in ITS where the core technologies and scenarios are described in [39].

Other projects have more specific characteristics; GeoNet [40] is one of these projects that gives a comprehensive specification of the GeoNetworking protocol to provide the geographic distribution of information in a vehicular network. The iTETRIS (Integrated Wireless and Traffic Platform for Real-Time Road Traffic Management Solutions) simulation platform project was created to deliver one of the first simulation capabilities on a large scale for ITS applications [41] by combining mobility and traffic communication.

Citymobil 1 and Citymobil 2 [42] addressed the development of vehicle communication to set up a driver platform for advanced automated transport systems in various European urban environments. Another European project such as ITERSAFE 2 [43] targeted the safety requirements by developing the cooperative safety system Intersection which can lead to a reduction of deadly accidents.

Various research papers have focused on three main security applications With Driver Support Systems [40], the onboard systems assist the driver on the road through the use of the most advanced information and communication technologies.

Presently, traffic problems are that the vehicles on the road can only be informed of the current traffic situation by using ineffective methods such as traffic lights or GPS systems. Therefore, V2X communication systems can ensure the transmission of information by offering possibilities to operate over a road network, in which vehicles may be informed about the current traffic situation at any time, and any location.

### 2.3.2 RF technologies challenges for vehicular systems

RF technologies present challenges that should be resolved to satisfy the quality of Service requirements of each application. Authors in [44], [45] have studied the challenges that affect RF technologies:

### **2.3.2.1 Latency limitations**

One of the main challenges in creating vehicle communication protocols is to achieve low latency under the impact of vehicle speed, poor connection reliability and fast-changing topologies. The result of RF technology in [46] shows that it is unable to meet delivery requirements when a node resends messages to its neighbour's node, and we have seen the worst performance in high-density scenarios.

### **2.3.2.2 The priority of safety packets**

The second challenge is the priority of safety packets that have the highest priority. That is why road safety packets must be transmitted before any other package. The focus of the largest part of the research activities has been on how to handle and give the highest priority to the emergency type of data packets.

### **2.3.2.3 Data security**

Illegal use of the radio spectrum of vehicular communications and potential violations are analyzed and risk-managed. The authors of [47] have proposed solutions to deal with these security issues, but the behaviour of the attackers is not taken into account. In [48], the authors have worked on a solution that is seen as a compromise between authentication and privacy when the communication system has to transmit the information communicated and the source of the data to certain authorities.

### **2.3.2.4 The problem of hidden terminals**

In wireless vehicle networks, the hidden terminal problem is caused by a hidden node (vehicle) that is seen and reachable from a certain wireless access point, without being detectable from other nodes (vehicles) that have a common communication channel and use the same AP. This problem is considered the main issue faced by the ad-hoc network.

## **2.4 Visible light communication for ITS**

### **2.4.1 Visible Light Communication**

Visible light communication is considered to be the preferred technology overall OW technologies due to the presence of an LED lighting system in roads and infrastructures [49], which results in a low-cost implementation [50], in addition to the location service of the vehicle which is provided by high precision positioning [51]. Moreover, the vehicle's local status can be exchanged by vehicles using the on-vehicles front and rear lighting systems [52], [53].

The most appropriate technology used for heavy traffic situations, such as congested cities or highways, is the VLC. The IEEE 802.15.7 [54], [55] standard is dedicated to short-range optical wireless communications using visible light. According to the standard, IEEE 802.15.7 provides three types of PHY layers depending on the applications and data rates requirements. The first layer (PHY

1) is reserved for outdoor applications with low data rates between 11.67 kbps and 267 kbps. The second and third layers (PHY 2 and PHY 3) are intended for indoor applications with medium data rates between 1.25 Mbps and 96 Mbps.

VLC applies the electromagnetic spectrum in the range of wavelengths 380 to 720 nm [55] as we can see in figure 2.7.

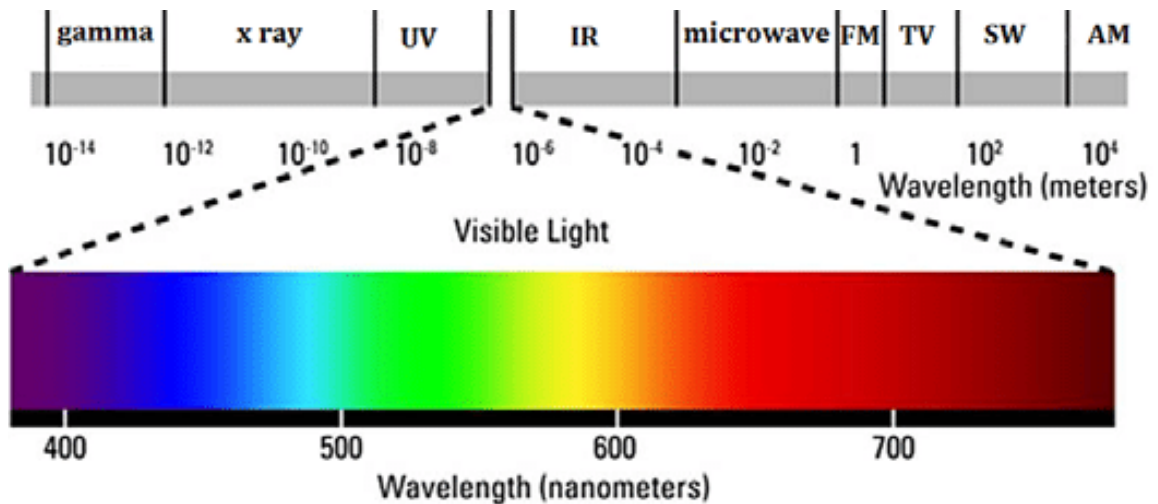


Figure 2.7: VLC electromagnetic spectrum

### 2.4.3 System hardware

The VLC hardware system is presented in this section. the transmitter and receiver components are used by taking into consideration the external conditions to ensure the QoS.

#### 2.4.3.1 VLC transmitter

The transformation of digital data into optical data is handled by the VLC emitters via the channel. The main functionalities of VLC transmitters are light emission and data transmission. The emitter unit consists of three principal hardware components, LEDs with focal lenses, a control circuit, and a microcontroller Arduino.

At transmitting and receiving units the VLC data processing is carried out using an Arduino microcontroller. This inexpensive microcontroller is by default unable to deliver the necessary current and voltage to allow rapid LED switching. To overcome this limitation, a basic circuit has been employed to allow a significantly higher amount of current to be switched at a very fast frequency.

The Arduino microcontroller is a cost-effective and feasible solution. the microcontroller provides a viable and cost-effective. the microcontroller can give sufficiently high performance to guarantee reliable and stable functionality with lower complexity.

The performance of the VLC transmitter unit is based on the physical characteristics of the LEDs, where the data transmission rate is highly dependent on the switching speed and capabilities



of the LED. Besides, the range of transmission depends on the visual transmission power that can achieve, a lighting pattern and the size of the sensitive aperture in the receiver.

### **2.4.3.2 VLC receiver**

On the receiving side, the purpose of implementing VLC was to obtain data from the optical signal received. The parts of the optical receiver include visual filtering, photo-detection, amplification, analogue-to-digital converter (ADC), demodulation and decoding.

The VLC method at the receiver end is mainly related to the amount of current generated by the PDs, which is an accurate measure of the optical beams detected. This current will be switched to the appropriate levels of voltage and then treated in an amplification stage, and finally demodulated and decoded using the same low-cost Arduino microcontroller that was used in the transmission unit [56].

As the whole VLC system is very sensitive to the amount of received noise and the interference of signal, the VLC receiver design requires maximum attention. Besides, the VLC receiver can be affected by any source of artificial or natural light falling into the field of view (FOV) of the receiver. The main objective of the VLC receiver's design is to improve the performance of the received signal, specifically the SNR level which represents the ratio between the amount of signal detectable by the transmitter and the channel noise. When selecting the VLC components, a trade-off between achieving a high SNR and a low-cost efficiency for implementation is introduced.

## **2.4.2 VLC implementation system**

In the following section, to achieve the VLC transmission and vehicular lighting functionality, the light emitter must employ high-switching light sources such as LEDs. The primary concern for the brake light and the receiver end will be optimizing the signal-to-noise ratio (SNR) level in presence of high interference level.

The transmitter and receiver end consist of 2 sections, electrical and optical as shown in figure 2.8, where the communication medium between them is the channel. The binary data on the transmission side is modulated and transformed into an electrical signal; this signal is then converted to an optical beam using LEDs to transmit the information to the VLC link. After propagating via the optical medium, the receiver picks up the optical signal with the help of a PD, which converts it into an electrical signal before demodulation.

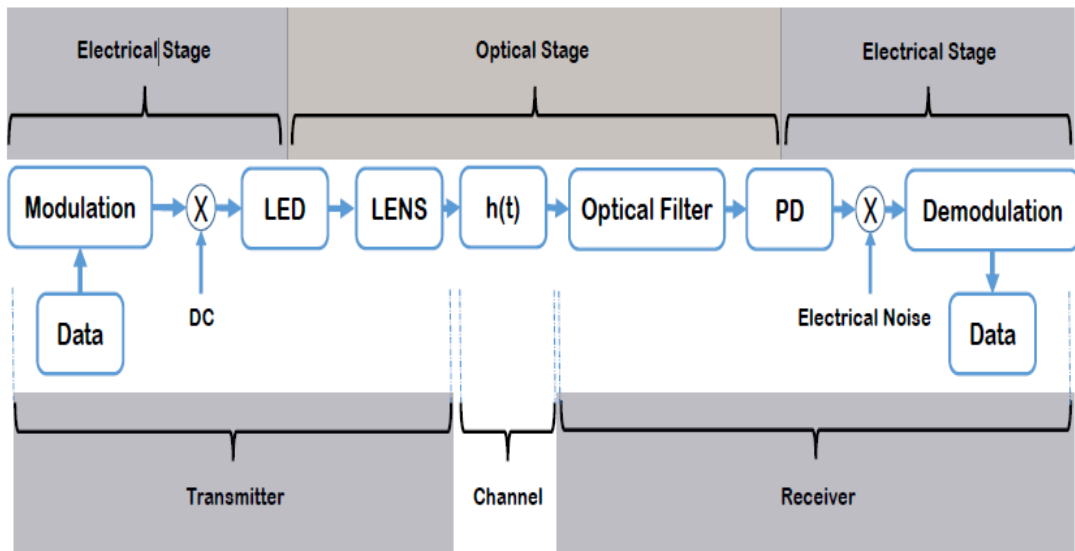


Figure 2.8: High-level overview of VLC [56]

### 2.4.4 VLC topologies

IEEE 802.15.7 standard includes three main access network topologies as shown in Figure 2.9:

- Peer to peer (P2P)
- Star
- Broadcast.

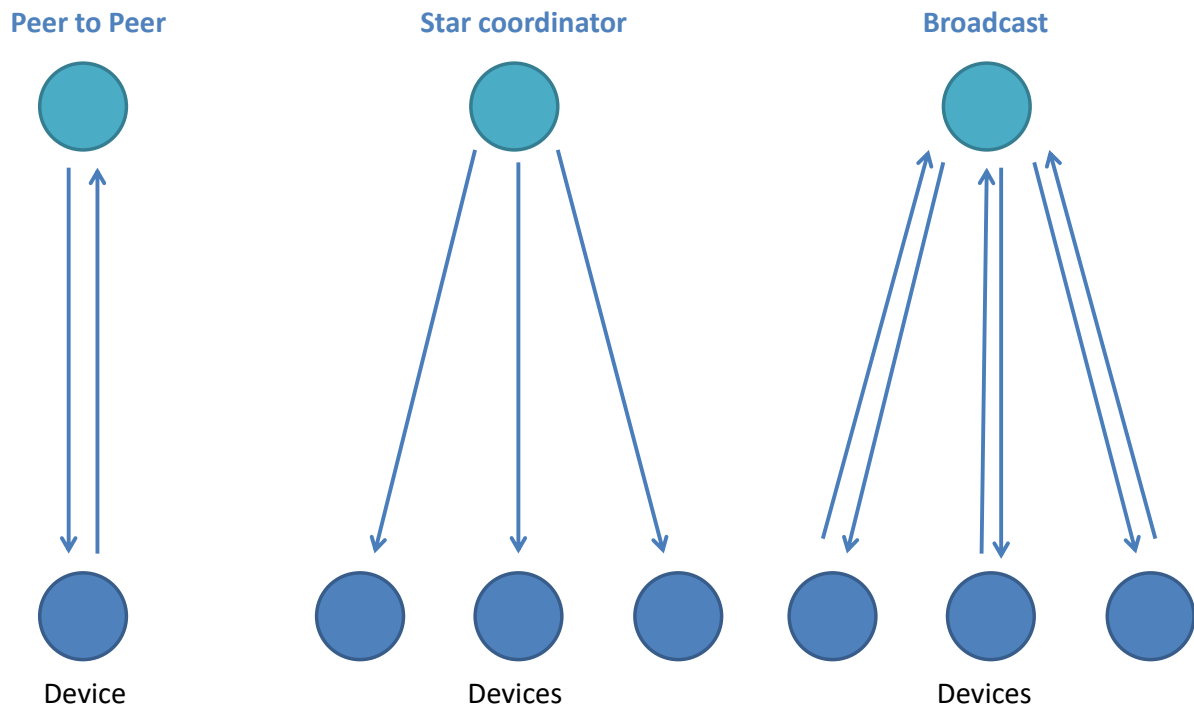


Figure 2.9: IEEE 802.15.7 standard visible light communication medium access topologies [54]

With the P2P topology, each device can communicate directly with all of its neighbour's devices. This is why one of the two nodes reacts as a coordinator, and usually, it is the node that initiates the communication.

The second topology is the star topology; this topology is responsible for controlling communication. Using the star topology, the devices will form an integrated network with a specific VLC identification. Communication between the devices is only possible for the device that joins the network; the other devices have to wait for the coordinator to let them join.

The third topology is the broadcast topology, which involves transmissions from one node to another and vice versa, without creating a network. This type of transmission is considered unidirectional where no receiver address is required.

### **2.4.5 VLC advantages and challenges**

The challenges associated with RF radio technologies have raised the attention of the industry and research telecommunications companies to VLCs. VLC offers higher bandwidth using an individual medium and offers different channel features. VLC offers several advantages over RF technologies:

- Unlimited bandwidth
- Free spectrum license range available for instant usage
- Secured information sharing protected against being intercepted or monitored
- Spatial Reusable enabling a significant enhancement of the flow rate
- No electromagnetic interference
- Lower power consumption technology
- Low complexity and cost: vehicle LEDs, traffic lights and streetlights are already available
- High precision positioning: VLC can decrease the positioning error to few centimeters
- Improving the link quality: VLC avoid the congestion problem because only neighbouring vehicles receive the information
- Scalability: VLC considers a small number of users only
- Security: attackers should be in the transmission range which is very difficult in the VLC case

However, the VLC performance is faced with several challenges that should be solved to achieve the desired QoS.

#### **2.4.5.1 Noise resistance**

The major challenge for outdoor VLC is the activated light sources that interfere with communication. The entire light sources have the same effect of degradation in the optical wireless channel. For this reason, the IEEE 802.15.7 standard [57] has pushed the communication to a higher band where the impact of the existing light source is less important. More specifically, for VLC

outdoor applications, the standard includes the use of 200 kHz and 400 kHz. In addition, the environmental condition (sunlight, snow, or heavy dust) is considered a powerful source of the noise. The noise effect is related directly to the FOV. Therefore, the most efficient solution to face this problem is narrowing the FOV [58].

#### **2.4.5.2 Increasing the communication range**

The second main challenge of the VLC in vehicular systems is the communication range. Since long-distance communications will result in low power signals and low SNR level in the receiver which is related to the interference problem. By studying the different traffic situations, the inter-vehicle distance varies from less than 35 m in the congestion area to a maximum distance of 160 m in a rural area [59]. Consequently, to be completely compatible with the automotive field, the communication distance should be considered as a challenge and needs to be enhanced.

#### **2.4.5.3 Enhancing mobility**

As mentioned before the SNR is affected by background noise which can be reduced by having a LOS and reducing the distance between the transmitter and receiver. However, narrowing of the receiver FOV will reduce mobility. The authors of [60], [61] have proposed a solution based on narrowing the FOV of the photodiode receiver, an inexpensive camera for the transmitter. This solution includes the advantages of photodiode and camera receivers but maintains a compromise between mobility and cost.

#### **2.4.5.4 Distance measurement and visible light positioning**

Usually, the Global Positioning System (GPS) is the most widely used tool for determining position. However, GPS is considered to be poorly performing in urban areas due to blocked links and multipath [62]. For these reasons, vehicles have replaced GPS with different solutions. One of these solutions is the VLC that is not used only for illumination and communication, but it could also be used to achieve high-precision positioning.

GPS is based on the arrival time difference (TDOA) between two received signals. Similar to GPS, by using the headlights and the taillights and repetitive on/off keying sequence to determine the phase difference of arrival, the VLC can calculate the distance between two moving vehicles based on the relative velocity.

#### **2.4.6 Research Literature**

Kanagawa [63], [64] is considered the first study to investigate the possibilities of deploying visible light, highlighting and encouraging the use of LEDs for indoor and outdoor communication. Specifically, this study explored for the first time the use of VLC in safety ITS applications by delivering traffic information between vehicles and traffic lights. This research was applied to other ITS applications in OMEGA [65] and D-Light [56].

An experimental demonstration of the collaboration between V2V and V2I communications has been proposed in [66]. This demonstration reached the promising BER of  $10^{-7}$  for both communication parities with improved error detection and correction codes.

Furthermore, numerous projects are being created around the world to study the application of VLCs for ITS. Examples of research projects that target the reduction of road infrastructure include Prevent and CALM [33] projects. The Portuguese government has been financing a research project called VIDAS [67], which applies VLC approaches to intelligent driver assistance systems. VIDAS proves the feasibility of providing a low data rate information link between LED traffic lights and vehicles. The results show that for particular atmospheric conditions, a BER of less than  $10^{-6}$  can be obtained for a communication range of 20 meters.

Moreover, Liu [68] is the main component considered for the realization of VLC networks. This project takes into account the requirements of the outdoor environment where the experimental results are implemented using network simulators (NS2). The Liu project demonstrates that the VLC system can satisfy the accessibility requirement for V2V communication in high-density traffic conditions.

The authors in [69] examined a collaboration application involving the traffic infrastructure and vehicles using VLC, introducing a prototype of vehicle systems that focus on improving the safety of traffic communication. Another study is done in [70] that is being carried out on VLC/LiFi communication in ITS systems that aims to integrate a system designed for platoon allowing a simultaneous V2V range measurement and data transmission using vehicle headlights and rear lights.

A new application is added to the autonomous vehicular component called photovoltaic (PV) receivers [70] as we can see in figure 2.10.

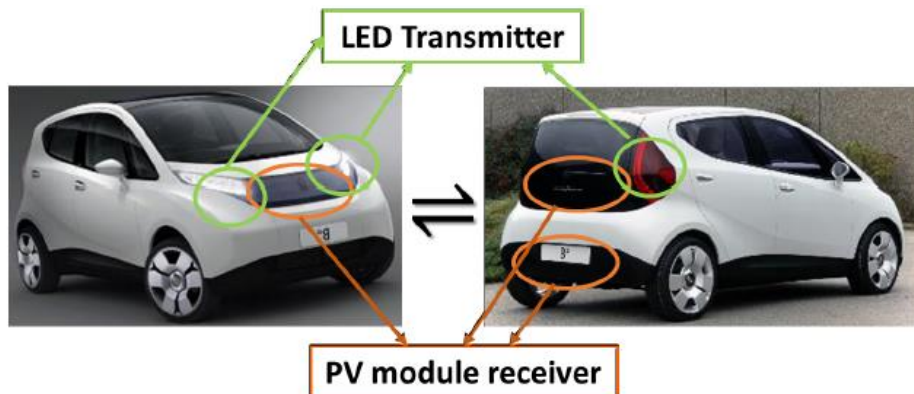


Figure 2.10: LiFi V2V communication using PV receiver

PV receivers solve the problematic situation and improve LiFi communication in outdoor conditions and allowing the high data rate (upper than 71 Mbps), the PV may be able to obtain data and from road traffic lights and street lamps and at the same time vehicles can communicate with surrounding vehicles using PV.

Table 2.1: An overview of the research works on VLC in ITS

Projects	V2V	V2I	BER	Communication range	Safety application	Data rate
Akanegawa	✓	✓			✓	
OMEGA/D-light	✓	✓			✓	
[66]			✓			
Prevent/CALM	✓	✓				
VIDAS			✓	✓		
Liu	✓					
[69]	✓	✓			✓	
Photovoltaic	✓	✓				✓

The above table indicates the features of each research work tackling VLC in ITS. These features are communication range, safety application, data rate, V2V and V2I.

## 2.5 Conclusion

This chapter was dedicated to the presentation of Intelligent Transport Systems, which is the mainframe of our thesis research studies. First of all, we introduced the ITS focusing on the vehicular communication modes, vehicular network components, the different types of applications that can be used in ITS, and the different types of communication technologies.

Afterwards, we surveyed the RF technologies and the visible light communications envisioned for vehicular networks. We performed a literature survey of the research projects, the use cases, the application scenarios, the issues and challenges faced by each communication technology. Since our thesis focuses on VLC performance, we have tackled in detail the VLC architecture.

The next chapter details the platooning concept, along with platooning formation algorithms in ITS that aim at reducing vehicular congestion.

## 3. Chapter 3: Vehicle formation strategies

### 3.1 Introduction

The ad-hoc network is built without any centralized control or infrastructure. It consists of a set of nodes where the decisions are taken by specific nodes. This network is able to detect the presence of other devices and perform the necessary set-up to facilitate communication. Each node has the opportunity to transmit and receive (transceiver), which enables it to communicate in its coverage area.

Regrouping of nodes may take several forms, such as the grouping of platoons or clusters. Different algorithms are used to create clusters or platoons according to their needs. These algorithms are considered efficient according to different parameters: the battery lifetime, speed of the node, the packet delivery ratio, latency. Furthermore, the efficiency of an algorithm is directly related to the choice of cluster head or platoon leader that affects the communication between different clusters or platoons.

This chapter introduces the different vehicles formation strategies. We work in section 3.2 on the first type of vehicular grouping “cluster” with the different cluster algorithms and the cluster head selection. This method is considered a mandatory strategy before starting with platooning algorithms. In section 3.3, we shed the light on platoon formation strategies, the benefits of using platoon and the classification of platoon strategies. Finally, we conclude the chapter in section 3.4.

### 3.2 Vehicle clustering

Wireless communication technology leads the way to the growth of wireless sensor networks (WSN) [71]. WSNs consist of several sensor nodes that communicate with each other using a variety of wireless technologies. WSN routing protocols are categorised into three classes: flat routing, location routing and hierarchical routing.

In a flat network, all nodes have the same task and play the same functionality (performing the detection activity) [72]. The flat routing algorithm is suitable for small-scale networks [73], [74]. However, due to resource limitations, large scale networks are less desired. Location routing is based on node positions in a specific area, which is considered an inefficient technique due to the high number of nodes in a large-scale network compared to the geographical area. In hierarchical routing, each node has its functions, and nodes are arranged in different clusters according to particular demands. Scalability, node lifetime and energy efficiency are parameters that determine cluster creation and the choice of cluster head.

When network scalability and efficient communication are needed for V2V communications, clusters are considered a suitable technique. Cluster routing [75]–[77] is an efficient approach to select high-energy nodes (or vehicles) to process and send data, while low-energy nodes are used to detect and send information to cluster head (CH). These properties support scalability, maximize lifetime and minimize energy.

### 3.2.1 Cluster formation algorithm

According to recent clusters surveys, nodes regroupment algorithms are mainly classified according to their main application [78], [79]. This approach is logical, as the design of a clustering algorithm is usually strongly affected by the application in which it is used. Several algorithms have been reported in the literature for specific application, while others are designed to meet the performance requirements of a very wide and varied set of applications.

The integrated technologies in intelligent vehicles allow the improvement of vehicle position that helps in cluster formation. The different propositions of clusters are based on the position and the mobility using the localisations technologies. Two essential steps should be taken into consideration before creating the cluster architecture: control the number of hops and control the number of nodes in each cluster [80].

#### 3.2.1.1 Control the number of hops

The DCA (Distributed Clustering Algorithm) and DMAC (Distributed Mobility-Adaptive Clustering) algorithms [81] allow the formation of clusters. In DCA, the cluster head is defined as the node with the highest weight. The weight can represent the degree of a node, the inverse of its average speed, an identifier, etc. This algorithm is well adapted to ad hoc networks with static or quasi-static topology. The DMAC algorithm is more suitable for dynamic networks as it introduces a cluster maintenance algorithm that reacts to changes in MAC-level topologies. Besides, it allows for a larger number of clusters, ensuring a more stable hierarchical structure.

#### 3.2.1.2 Control the number of nodes in each cluster:

A cluster can also be limited in size by limiting the number of nodes in a cluster. In fact, maintaining clusters of balanced size helps to balance the load of the communications between nodes [82] and reduce collisions within the group. In [82], if the cluster exceeds the maximum limit size, it is divided into two by the election of a new cluster head. If the cluster is considered to be too small, a node at the edge of a larger neighbouring cluster is recruited.

Different techniques are used to create clusters based on vehicle MAC layer, vehicle traffic dynamics, the relative distance between vehicles, the direction of movement, relative speed and direction.

#### 3.2.1.3 Traffic dynamics in VANETs

In a highly dynamic network such as VANETs, the mobility of nodes disturb the cluster structure [83]. This instability leads to higher numbers of messages exchanged and poor performance. To maintain the stability of the clusters, the position of the vehicles is not sufficient and many proposals use both spatial and temporal information to understand the particular dynamics of moving vehicles and to build clusters with a longer lifetime.

The idea is to group the vehicles according to their spatial or temporal dependencies. The spatial dependencies are represented by the position of the vehicle, its distance from another point, its



direction of travel or the quality of its radio link with another vehicle. Temporal dependencies are the speed of the vehicle and especially the relative speed between two vehicles.

Technologies integrated into intelligent vehicles make it possible to improve the accuracy of their position, in particular through positioning on the map and onboard sensors such as radar range finders [84], [85]. The various proposals for clusters based on position or mobility use these precise location technologies.

#### **3.2.1.4 Clustering according to the lane in which the vehicle is located**

Authors in [86] adjust the position of the vehicle with exact knowledge of the lane in which the vehicle is travelling. The lane is obtained by comparing the position of the vehicle with an accurate street map. A cluster is built for each lane for an emergency braking assistance application based on its future direction after an intersection: "turn left, right or straight ahead."

#### **3.2.1.5 Clustering according to the relative distance between vehicles**

Another clustering criteria derived from the position of the vehicles is the relative distance between vehicles or their location within a given geographical area [87], [88]. The objective is to limit the broadcast of messages in a constrained space, whether for routing or for ITS applications with a local reach.

#### **3.2.1.6 Clustering according to the direction of travel (movement-based)**

It was noticed that vehicles travelling in the opposite direction could not communicate very long [89], [90]. Even worse, grouped in the same cluster, these vehicles have a very short residence time in the cluster and make the structure unstable. The direction is obtained from the history of the vehicle's positions, with or without reference to a map or the angle of travel in relation to the north. Therefore, many works use steering as a criterion for grouping vehicles [91]. In [91], the Vehicle-Heading Based Routing Protocol (VHRP) creates groups of vehicles according to their direction with the leading vehicle as the cluster head. Within the cluster, a path is established between all its members, with priority given to the quality of the radio links. The change of direction and the breaking of the radio link cause a change of cluster.

#### **3.2.1.7 Clustering according to speed and relative speed**

A special feature of VANET networks is the speed at which vehicles travel. This speed is, therefore, taken into account when grouping the vehicles in a convoy because a group of vehicles of almost identical speed is a relatively stable structure. The mobility criterion is more precise and is called relative speed. This criterion improves the stability of clusters. Thus, [92] introduces the concept of aggregate mobility to improve the stability of clusters. The authors propose a relative mobility metric for MANETs. Relative mobility is measured by the Received Signal Strength (RSS), which is an indication of the distance between the transmitter and the receiver.

### 3.2.1.8 Clustering according to position, speed and direction

Authors in [93] group the vehicles using an affinity function that considers both the position of the node and its speed. For different cluster update intervals and different speeds, [93] shows stability metrics such as average cluster head lifetime, the average lifetime of members, the rate of change of cluster heads and the average number of cluster members compared to the MOBIC protocol [92]. The results show that their approach greatly improves the stability of clusters.

Authors in [94] use the same principle but propose a more precise mobility metric called ALM (Aggregate Local Mobility) with the fairly realistic assumption where every vehicle knows its position. Similarly, vehicles include their position in HELLO messages broadcast in their coverage area. The ratio between two successive distances defines relative mobility between two vehicles. ALM forms coherent clusters of vehicles with the same speed and the same direction whose performance analysis demonstrates their stability.

Each cluster needs a cluster head which must have a long lifetime and be connected to the largest number of nodes to be considered a stable cluster. In the next section, we will present the different cluster head strategies used in the literature.

### 3.2.2 Cluster head selection technique

Cluster head selection ensures the stability of any cluster according to different criteria as we can see in figure 3.1. In the next subsections, we introduce the different cluster head techniques.

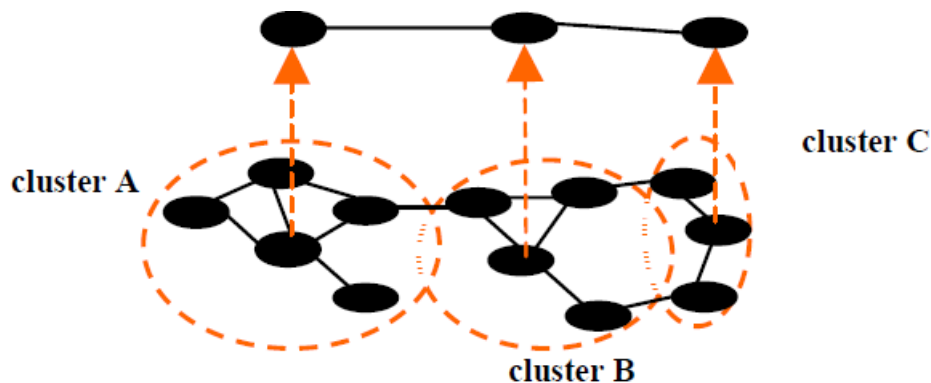


Figure 3.1: Cluster and cluster head in VANET

#### 3.2.2.1 Lowest ID

The lowest ID algorithm consists of cluster head selection using an automatic sequence of a fixed vehicle identification attribute. The cluster formation is executed using the cluster head selection at the node level. During the clustering phase, each node in the network diffuses its ID to all accessible nodes. Each user selects the node with the lowest ID as the cluster head. Authors in [95]–[97] discuss in details the Lowest ID method that is known by its stability in MANET applications. The node that has the lowest ID in each cluster is considered the cluster head and stores the information of all other nodes where the vehicle with the highest the lifetime has the lowest ID.

### 3.2.2.2 Highest-Degree Algorithm

The selection of cluster heads using the highest degree algorithm is based on the degree of the node in the network where the node with the highest degree is the cluster head [98]. This technique aims to cover larger cluster nodes. The degree depends on the motion of each node. For this reason, the cluster that uses the highest degree algorithm does not support the same cluster head for a long time, which leads to instability.

### 3.2.2.3 The closest position to average (CPA) [99]

Using this technique, the cluster head is selected according to the position of the vehicle, which must be close to the average position of all vehicles. The utility function steps are implemented using this method:

- Each vehicle must define the local broadcast area and follow the candidate cluster head set C. All vehicles in the broadcast area are qualified as candidates for the selection of a cluster head.
- Each user must rate the CPA function using the set C and the information obtained by broadcast.
- The head of the cluster is chosen in descending order of CPA Value. The petition for cluster head is circulated between the chosen vehicle. If the selected vehicle refuses the petition, then the vehicle with the next highest utility is chosen and this step should be done again.

### 3.2.2.4 Weighted Utility Function (WUF)

The WUF aims to enhance the clusters' structure to achieve greater cluster stability. This method is based on a couple of several parameters with some weighting factors.

$$Utility = W_1.ID + W_2.\Delta D + W_3.SD + W_4.AVT$$

$$\sum W_i = 1$$

- **$\Delta D$  degree difference of each vehicle:** it reflects the stability of surrounding vehicles
- **SD Distance function:** Sum of distance with its neighbours
- **AVT Average velocity function:** it gives a measure of mobility
- **IDs** are assigned based on the mobility and energy state of the nodes
- Calculate the utility of all the vehicles and the one with the lowest utility is chosen as the head of the cluster

### 3.2.2.5 MOBIC algorithm

The vehicle that has the lowest aggregate mobility value in its neighbourhood coverage is selected as a cluster head and then broadcasts all messages to the surrounding vehicles that have the opportunities to join the cluster. By using the MOBIC algorithm [100], clusters with the maximum distance between cluster members are formed.

Table 3.1: summarized cluster and cluster head algorithms [101]

Algorithm	Strengths	Weaknesses
<b>Lowest ID</b>	Fast and simple Stable clusters	Small clusters Long cluster head duration
<b>Highest-Degree</b>	Most connected nodes Higher priority	Unstable clusters
<b>CPA</b>	Coverage distance of vehicles	Vehicles velocity is not taken into consideration
<b>WUF</b>	Distance between neighbours Velocity of vehicles Stable clusters	Long cluster head
<b>MOBIC</b>	Lowest aggregate mobility value Neighbourhood coverage	Unstable cluster High cluster size

## 3.3 Vehicle platooning

Vehicle platooning is a technique where highway traffic is organised into a group of close following vehicles called platoons and has several advantages. In the next subsection, we will highlight the benefits of using vehicle platoon, the platoon formation strategies, the classification of these strategies and the vehicle platoon maneuvers.

### 3.3.1 Benefits of vehicle platooning

The formation of vehicle platoons has several advantages. These benefits include increasing highway capacity and improving safety, reducing negative impacts on the surrounding environment and enhancing driver comfort [102], [103]. All these advantages are achieved by working on platoons parameters [104] that affect the road capacity as we can see in Figure 3.2:

- $d$ : inter-platoon distance
- $D$ : intra-platoon distance
- $l$ : vehicle length
- $V$ : vehicle platoon speed
- $n$ : number of vehicles in the platoon

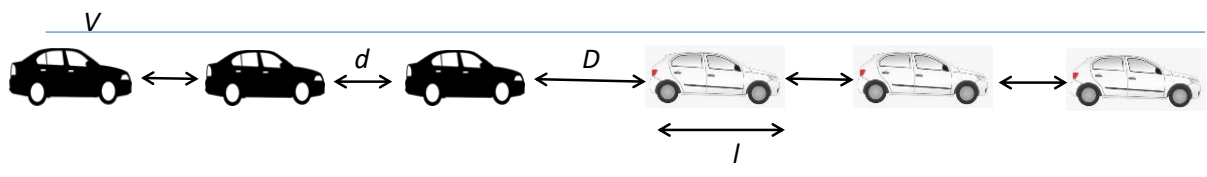


Figure 3.2: Vehicle platoons parameters

### **3.3.1.1 Increasing highway capacity**

The primary purpose of using platoon is increasing the highway capacity. The platoon achieves this objective by moving vehicles with a distance gap lower than the usual gap of manual drivers.

Unfortunately, the platoon system has never been implemented in reality. Most of the study cases done are based on simulation models. One of these projects, carried out by VanderWerf, studied the ability to grow demand for adaptive cruise control and cooperative adaptive cruise control vehicles to penetrate the market more effectively compared to manual driving [104]. They simulated a single-lane of 16-kilometre highway with entry and exit ramps every 1.6 kilometres. These simulations gave a capacity rating of 2100, 2150 and 4250 vehicles per lane per hour respectively.

### **3.3.1.2 Reduction of Environmental Impacts**

The traffic system contributes significantly to the production of global gases. In fact, the transport sector represents about 30% of the total CO<sub>2</sub> emissions in the United States in 2008. The transport sector is searching for ways to decrease fuel consumption and, thus, reduce environmental impacts.

Vehicle platooning is one of these options. The use of platoon vehicles decreases the air resistance and, therefore, the fuel consumption. This outcome has been achieved in both laboratory tests and field experiments [103], [105]. The results show that fuel efficient vehicle platoons are highly related to the location of the vehicle in the platoon and the operating distance.

### **3.3.1.3 Improved Safety**

Human error is the major cause of most accidents on the road. Indeed, drivers can be partially or totally responsible for more than 90% of road accidents [106]. High speeding, being distracted, tired and sometimes driving under the influence of alcohol are the reasons that can lead to human error.

The formation of vehicle platoons is actually considered to be one of the concepts that can enhance traffic safety. Any system that implements vehicle platooning using a combination of technologies can not only respond faster to dangerous situations, but it may also provide a traffic view extending beyond the field of view of the driver. This allows early awareness of risky situations and, therefore, enhances safety.

### **3.3.1.4 Improved Driver Comfort**

Driver comfort is the final benefit of vehicle platoon. The driver's tasks are linked to the level of vehicle automation. In particular, on long journeys on the highway, automated vehicles can reduce stress and allow the driver to concentrate on his work.

### 3.3.2 Platoon formation algorithm

The Adaptive Cruise Control (ACC) and the cooperative Adaptive Cruise Control (CACC) are the 2 vehicles systems that can be used in the vehicular platoon.

#### 3.3.2.1 Adaptive Cruise Control (ACC)

Adaptive Cruise Control [46] helps the driver by using the information from the preceding vehicle. Once the preceding vehicle is detected, the ACC system adjusts the vehicle's speed to get fixed time-gap without driver intervention. With the usage of the information from the preceding vehicle, the leader system is only able to detect vehicles in the line of sight, therefore, the ACC system is not able to measure the distance and the speed of vehicle delivery in front of the immediately preceding vehicle, behind the vehicle and vehicles in a different lane.



Figure 3.3: Adaptive Cruise Control [41]

#### 3.2.2.2 Cooperative Adaptive Cruise Control (CACC)

Cooperative Adaptive Cruise Control [47] improves the ACC capabilities and allows cooperation between vehicles through wireless communication, new control logic and GPS. CACC is considered the most recommendable system because it ensures road safety and information efficiency, which is the most critical issue in the area of the vehicular system.



Figure 3.4: Cooperative Adaptive Cruise Control [47]

The cooperation of vehicles build a platoon and may lead to a more efficient structure. Authors in [107] explore and study several platoon strategies. These strategies aim to increase the distance between vehicle platoon and maintain the platoon as a complete unit. This essentially involves grouping vehicles together based on their destination, and this can be done in several ways. The following strategies outline the formation of the platoon:

### 3.2.2.3 Destination Group (DG)

As everyone knows, all highway exits are assigned to a specific vehicle destination. By using DG strategy, each lane at the entrance ramp is assigned to appropriate destinations and can contain a specific number of vehicles. Every arriving vehicle queues up the lane. Once the lane contains the required number of vehicles or the time has expired, the platoon can be released into the highway.

Using multiple lanes at the entrance for the formation of platoons, like is used for the DG strategy as we can see in figure 3.5, may lead to smaller platoons on average or longer waiting times. Indeed, the total arrival rate is divided over the lanes. However, the arriving vehicles are not necessarily divided equally over all lanes, which results in variations in the average platoon size and waiting times. Another downside of multiple entrance lanes for platoon formation is the need for space to accommodate multiple lanes.

The entrance ramps are used to create the platoons using DG strategy as we can see in figure 3.5. The DG's strategy can result in small platoons and high waiting times. The total arrival rate is divided over the lanes according to their destinations, but these vehicles are not equally distributed over all lanes, which causes a variation in the platoon size and the waiting time between lanes.

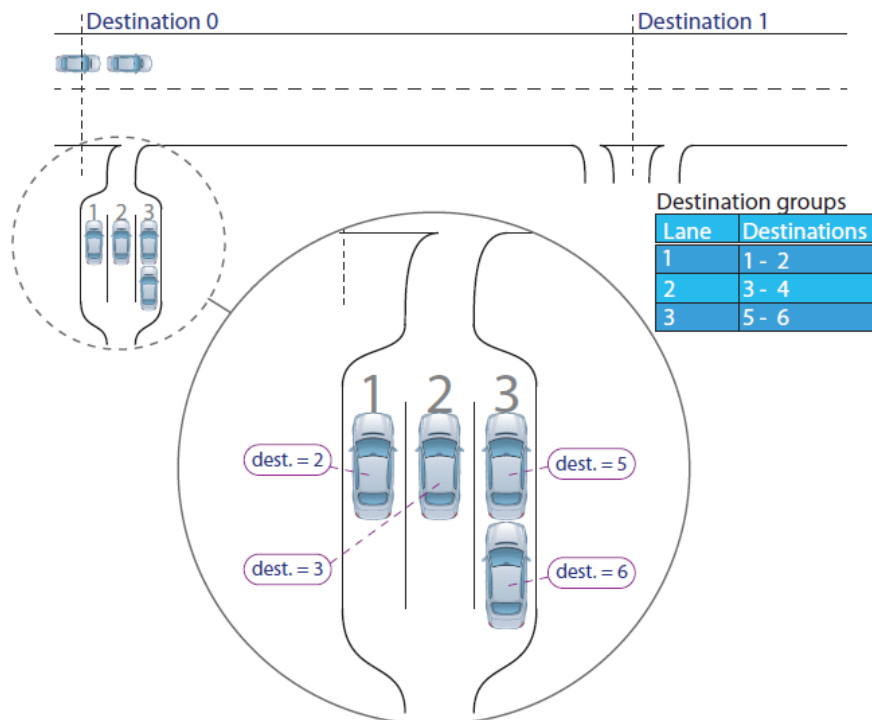


Figure 3.5: DG strategy

### 3.2.2.4 Dynamic Grouping (DYG)

DYG strategy may lead to form 2 vehicles per platoon as we can see in figure 3.6. By comparing this strategy to DG strategy, the average size of the platoons has been improved. By using the DYG strategy, the vehicle still has the opportunity to attach to more than one platoon. The destination similarity is in the criteria that let the vehicle assign to a specific platoon. If there is no accessible platoon and no free lane left, the platoon that waits the longest time should release the lane. The cleared lane is then used by the new arriving vehicle that creates a new platoon.

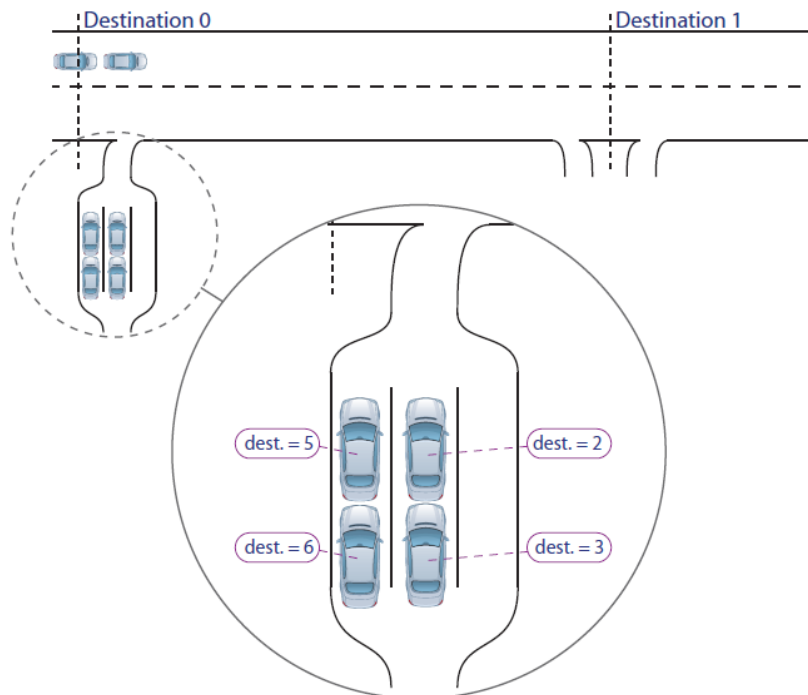


Figure 3.6: DYG strategy

By using the maximum range "r", the vehicles that have the same destinations form the platoon in DYG strategy. The small value of destination range indicates the similarity of destinations, lets the platoon be released faster and decreases the platoon splitting on the highway. However, the reduced destination range with a limited number of lanes will make the coverage of all destinations difficult.

### 3.2.2.5 Dynamic Grouping and Platoon Splitting (DGPS)

With DG and DYG strategies, the platoon is split up immediately after a vehicle reaches the first exit from its destination group. After splitting, the platoon is decomposed and each vehicle is driven alone on the highway. The difference between DGPS and the previous strategies is that the platoon using DGPS can continue driving on the highway even if the vehicles have reached their destination and left the platoon. Vehicles in DGPS are sorted in the platoon according to their destination where the leading vehicle has the farthest destination as it is shown in figure 3.7.

When sorting a vehicle into a platoon using DGPS, the last vehicle in the lane must have a greater destination distance compared to the arriving vehicle. If no lane is available and no platoon



meets the DGPS requirements for arriving vehicles, one of the platoons will leave the entrance ramp to the highway and a new platoon will be formed in the free lane. The platoon will move to the highway after a certain amount of time or after having a specific number of vehicles in the lane.

As shown in figure 3.7, using the DGPS algorithm, the last vehicle will leave the platoon first when it reaches its destination, which allows the platoon to continue driving on the highway without splitting up. The other vehicles in the platoon are not disturbed by this separation and the platoon can continue driving on the highway as one unit.

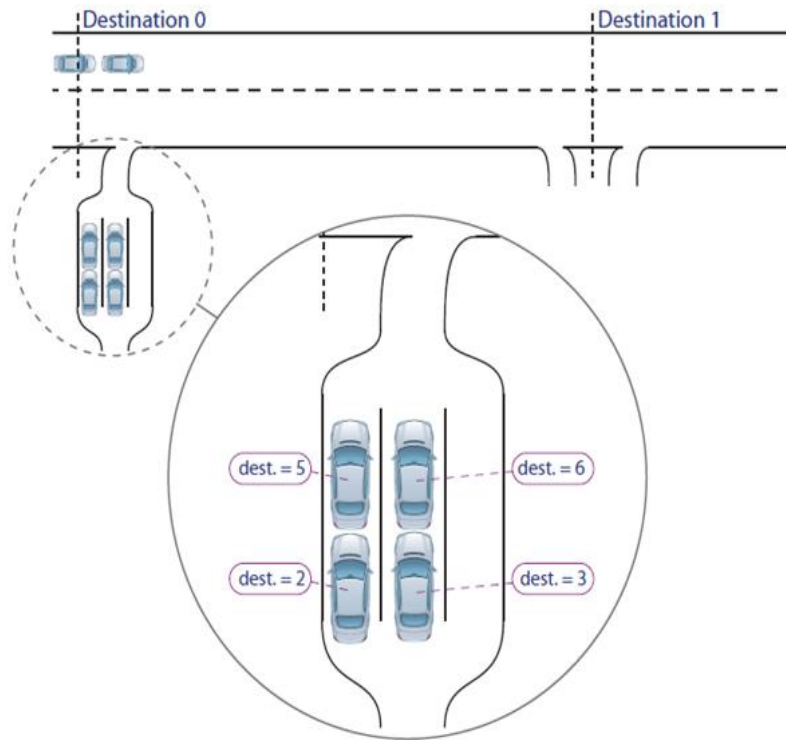


Figure 3.7: DGPS strategy

### 3.2.2.6 Random Assignment (RA) and the Dao strategy

The most basic formation strategy is the random assignment where arriving vehicles select their lane randomly. This strategy is similar to ad-hoc for vehicle formation algorithm.

A new platoon formation algorithm has been proposed in [38] called Dao that differs from the previous strategies. Dao algorithm is applied by each non-assigned vehicle that arrives at the merging point. This vehicle can communicate within its range with all vehicles and platoons. Using the communicated information, vehicles can be assigned to a platoon at the entrance ramp.

Dao's algorithm enhances the road capacity by finding an optimal assignment of merging vehicles at the entrance ramp into platoons as shown in figure 3.8. Dao algorithm performs a local assignment of arriving vehicles to platoons at the merging point, the point at which the entrance ramp merges into the highway.

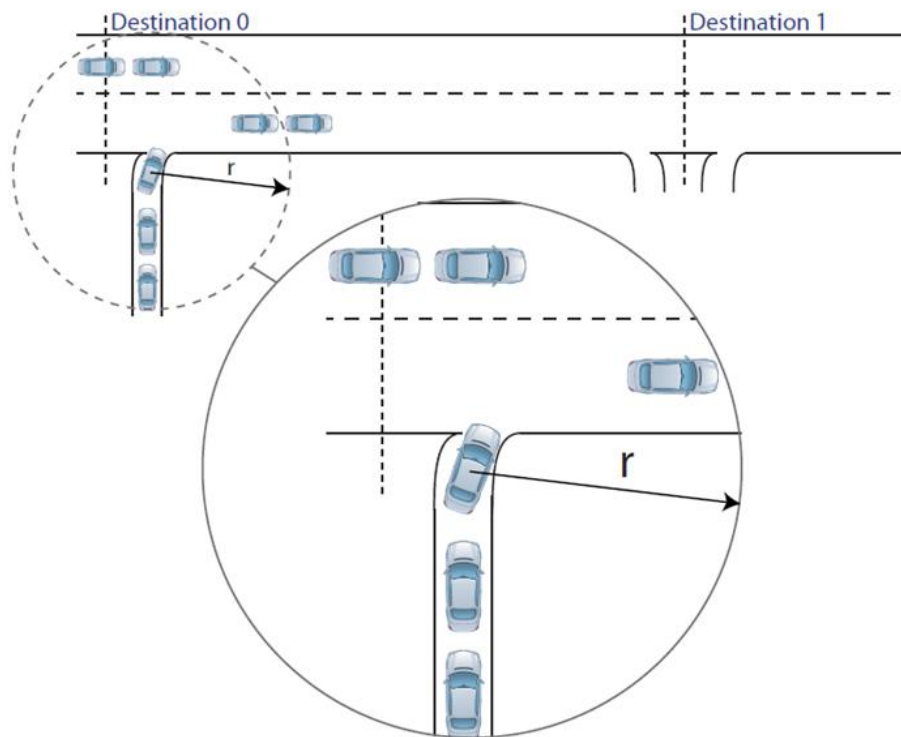


Figure 3.8: Intelligent platoon formation strategy [108]

### 3.3.3 Classification of Platoon Formation Strategies

The purpose of our classification is to provide a detailed view of the approaches that could be taken to form a platoon. It is based on the organizational policy type. We have 3 different classifications: Ad-Hoc formation policy, platoon sorting formation policy and destination ranging formation policy.

Starting with the first classification, the ad-hoc formation policy is where the vehicles are placed in groups together. The second strategy is the platoon formation policy, where the vehicles are classified based on their destination, thus enabling them to leave the platoon without splitting

the whole platoon after reaching the destination. The last strategy is the "Destination Ranging" formation where vehicles that have near destinations are grouped together.

Table 3.2: Classification of platoon formation strategies

Platoon formation strategies	Ad-Hoc	Platoon Sorting	Destination Grouping
RA	✓		
DGPS		✓	
DG			✓
DYG			✓
Dao			✓
ACC	✓		
CACC	✓		

The classifications of platoon formation strategies are visualized in table 3.2. CACC, ACC and RA strategy form platoons based on the ad-hoc networks. The DGPS strategy includes the policy of sorting platoons. Dao, DG and DYG strategies limit the destination range of vehicles in a platoon where the DG restricts this range statically and the DYG dynamically.

### 3.3.4 Vehicle platoon manoeuvres

In this section, we introduce the different manoeuvres where vehicles have the opportunity in these strategies to join or leave the platoon. The following section describes these manoeuvres.

#### 3.3.4.1 Joining platoon

Joining platoon is a term composed of two options. The first one is the combination of two platoons to form one unique platoon; the second option is the vehicle that joins the platoon. Figure 3.9 illustrates the situation where a vehicle accelerates to join the platoon after having the approval from the platoon.

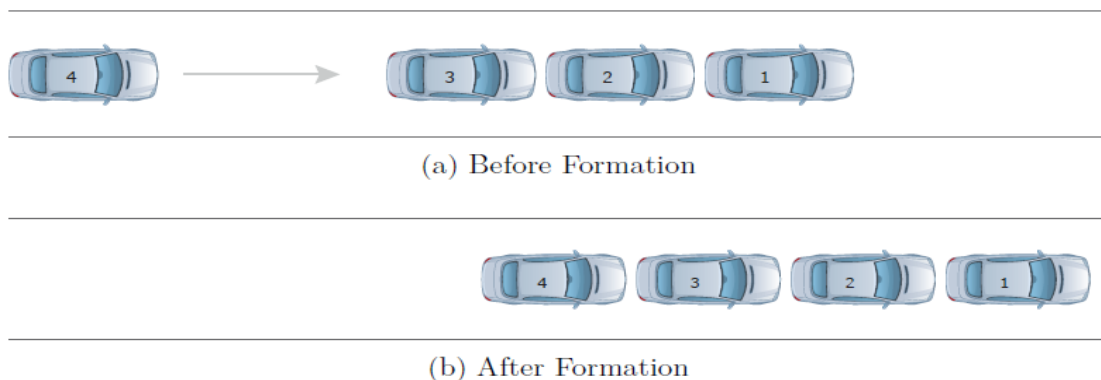


Figure 3.9: Joining the platoon [109]

### 3.3.4.2 Splitting platoon

The platoon split takes place when one or more vehicles leave the platoon. An example of a splitting vehicle is illustrated in Figure 3.10.

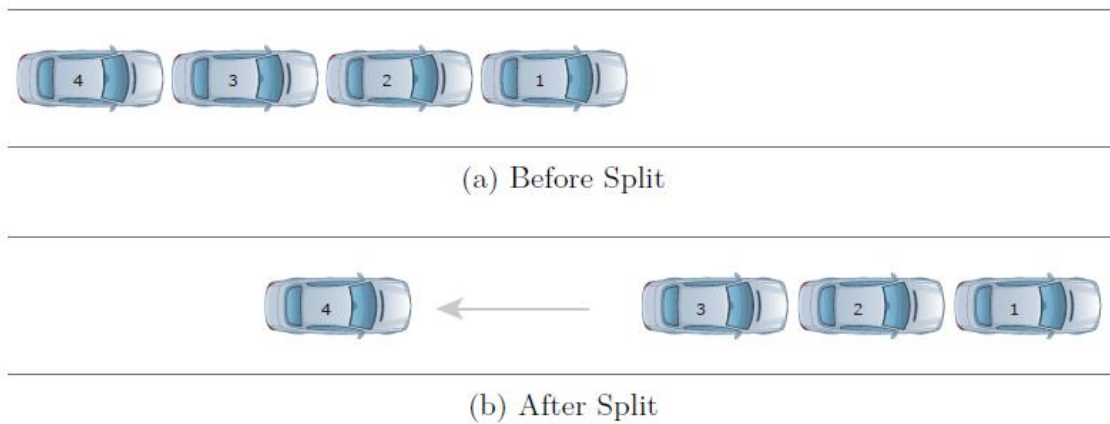


Figure 3.10: Splitting from the platoon [109]

## 3.4 Conclusion

Vehicular platoon is a group of vehicles that travel together on the highway. The leading vehicle is followed by several vehicles that closely match their speed to the leading vehicle. Platooning is an interesting solution to minimize environmental pollution and to make more efficient use of fuel and road space while enhancing safety and comfort on the road.

In this chapter, we have studied the different cluster formation algorithms and the different techniques used to select a cluster head. Then, we have introduced the platoon strategies with different advantages. Finally, we have presented the different platoon formation strategies and classified them according to an organizational policy.

Due to surrounding interference, the QoS of the vehicles communication link is affected. For this purpose, it is necessary to make a vertical transfer between the technologies to ensure the reception of packets, which will be discussed in the next chapter.

## 4. Chapter 4: Vertical mobility

### 4.1 Introduction

Handover study is crucial in deploying mobile transmission as it creates data sessions between mobile devices which are constantly on the move [110,111].

In heterogeneous wireless networks, vertical handover (VHO) plays a central role. In fact, designing a handover algorithm for heterogeneous networks becomes of paramount importance since it is responsible for providing better QoS and higher level of Quality of Experience to users moving seamlessly across different radio access networks.

This chapter presents vertical mobility. In section 4.2, we focus on the overview of handover phases. We introduce handover types and parameters in sections 4.3 and 4.4. The classification of vertical handover decisions is presented in section 4.5. In sections 4.6 and 4.7, we exhibit the different vertical handover algorithms and the analysis of these algorithms. In section 4.8, we highlight VHO algorithms using VLC before concluding the chapter in section 4.9.

### 4.2 Handover Overview

Handover is the process of moving an active call or data session from one cell of a cellular network to another. Handover is required in order to avoid service interruption, it takes different forms and consists of three phases [112] as we can see in figure 4.1:

#### 4.2.1 Handover initiation phase

During this phase, the user checks the decrease in signal strength or link quality. The data collected from the neighbouring networks of some parameters are required for the next phase. Some of these parameters are the signal to noise ratio, bandwidth, bit error rate (BER), and they are related to the current user statement like velocity and power consumption.

#### 4.2.2 Network selection phase

The collected information from the first phase will be used to provide a predefined selection mechanism. This selection mechanism is an open question where numerous research works in the literature offer different types of algorithms that will be studied in the next sections [113]. The network selection decision can be based on a specific algorithm or Fuzzy Logic technique.

#### 4.2.3 Handover execution phase

A major objective of this phase is supporting the user to provide a smooth handover between the existing and target network. During this period, the user is unable to receive or send data. This is known as handover delay. To maintain an adequate quality of service during handover, this delay must not be higher than a specific threshold.

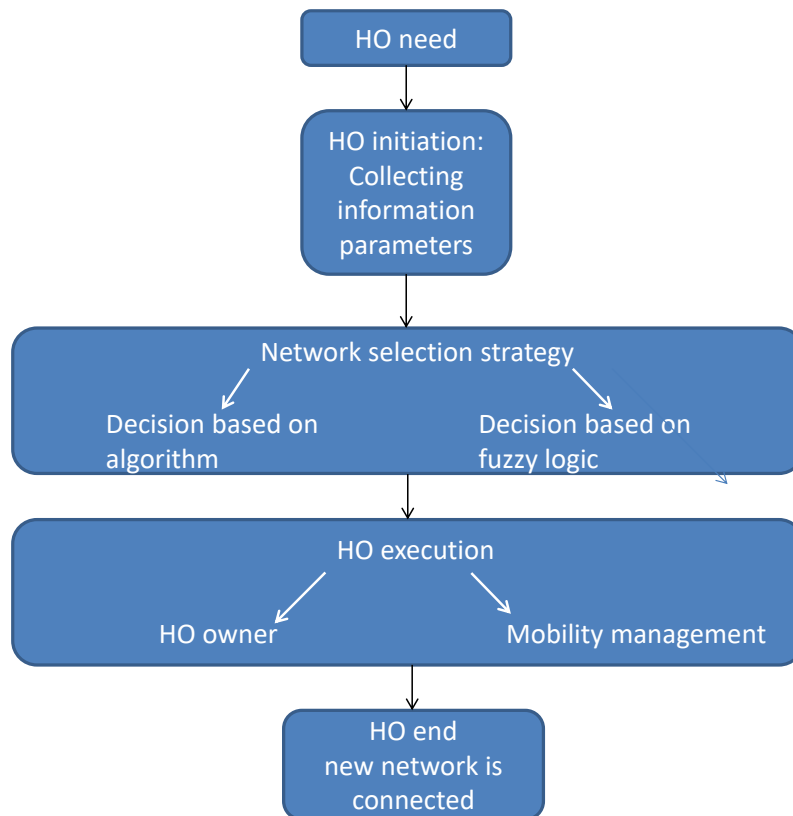


Figure 4.1: HO phases [114]

### 4.3 Handover type

Handover can take 2 different types: Horizontal Handover (HHO) or Vertical Handover.

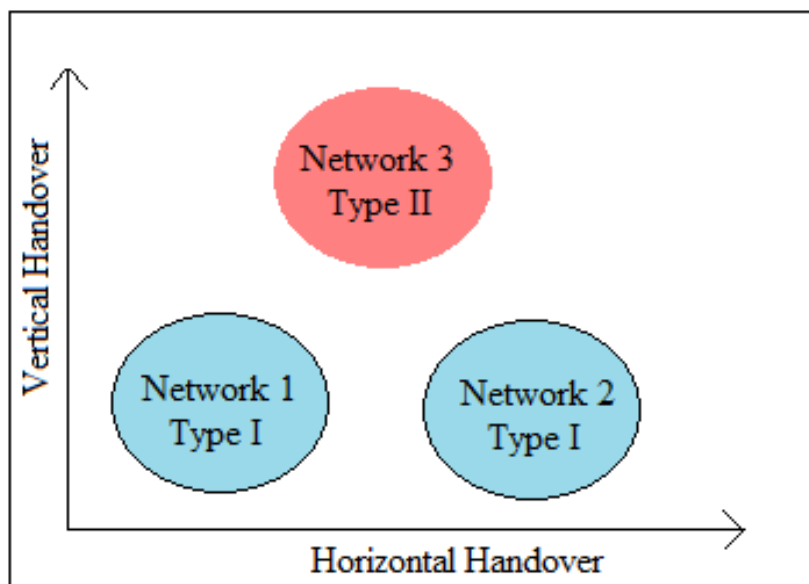


Figure 4.2: Vertical and Horizontal handover [114]

The first type of handover is the HHO process. It requires data transmission from one base station to another within the same RF technology. The data link layer and the network interface card are the necessary reconfigurations in the HHO.

The second type of handover is the VHO process, which consists of moving from one network technology to another. In other words, VHO is presented as the capability to transfer data between heterogeneous networks. The choice of an appropriate base station is the greatest challenge among all the existing candidates, without having any perturbation of data [115].

## 4.4 HO parameters

In HO, the user will decide to stay with the same current network, switch to a new base station in the same network “HHO” or to move to a new network “VHO”. This decision is based on several parameters known as network selection parameters, which are classified into 4 categories as shown in figure 4.3: network parameters, terminal parameters, user parameters, service parameters.

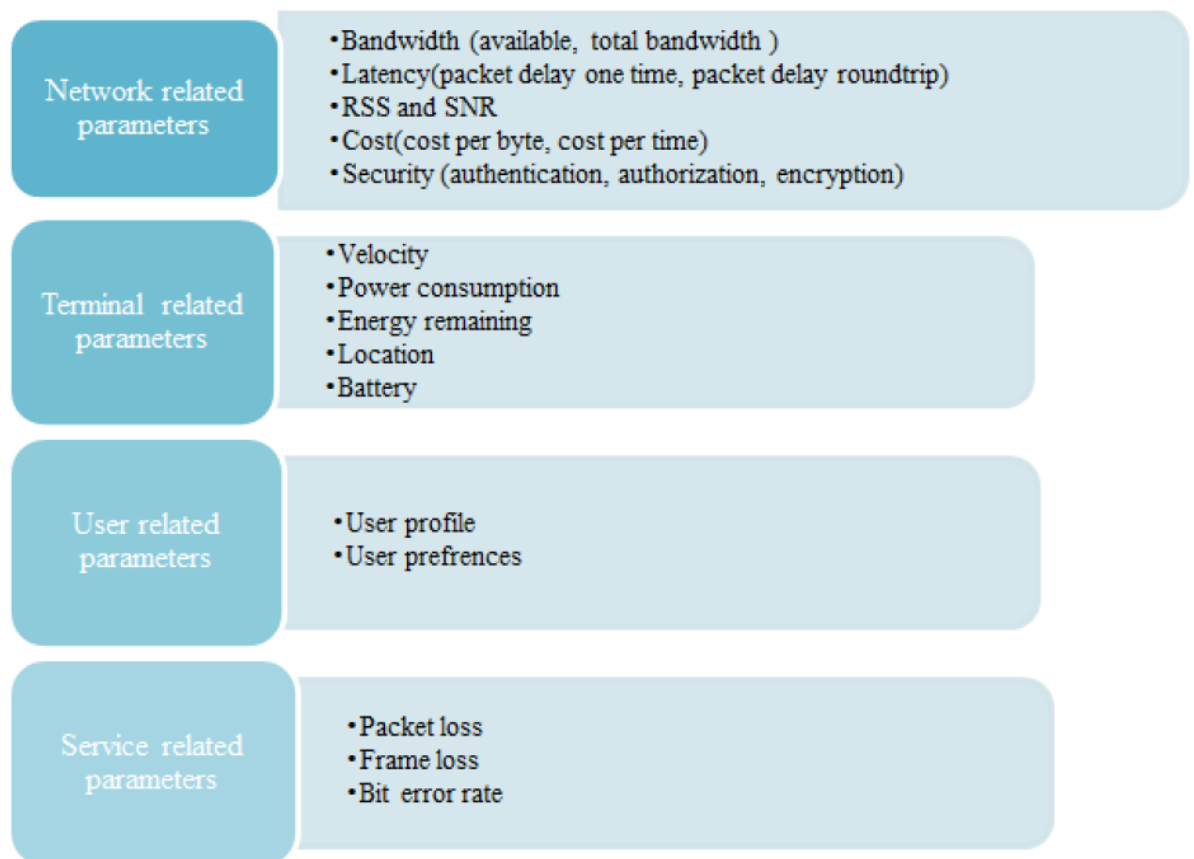


Figure 4.3: HO parameters [114]

Below is a brief explanation of several parameters used in VHO parameters:

#### **4.4.1 Received Signal Strength (RSS)**

The major network selection parameter for HHO algorithms is RSS. This parameter is considered a critical parameter because it can be easily measured, a good indicator of the network strength and the quality of the link [114]. However, RSS parameters are not suitable for VHO in a heterogeneous system, because networks have different channel coding, interference and power which makes RSS unmatched for the various radio access technologies.

#### **4.4.2 Network Connection Time**

It is the period during which the user must be connected to a specific network. The connection time allows the user to determine exactly the ideal time to start transmission, to ensure a good QoS and to minimise the number of handover failures, since a handover made at an inappropriate time may lead to a waste of resources and a handover failure.

#### **4.4.3 Handover Latency**

Handover latency is the time between the last packet received in the old network and the first packet arriving in the new network. This latency can affect QoS.

#### **4.4.4 Available Bandwidth**

Bandwidth is defined as the transmission speed of the channel in bit per second (bps). Bandwidth is an indication of traffic and network conditions. Usually, the network that has the highest bandwidth is the chosen one since the probability of interruption or blocking calls decreases as the bandwidth increases [116], [117].

#### **4.4.5 Power Consumption**

The power consumption becomes critical if the battery of the user is low. In this case, the network that can increase the battery lifespan is recommended for handover.

### **4.5 VHO Algorithms**

#### **4.5.1 VHO Algorithms based on RSS**

The received signal strength is the primary factor in RSS-based algorithms. Such types of VHO algorithms evaluate the RSS of the existing attachment point in comparison with the remaining ones to make decisions about the handover. Authors in [122] propose a handover between 3G networks and WLANs by matching RSS metrics with an estimated duration or with the available bandwidth of the competing WLAN. This method may be illustrated by the following two scenarios.



In the first scenario, whenever the user switches from the area covered by a WLAN to a 3G network, the handover to the 3G network is activated. If the mean RSS of the current WLAN network connection drops below a predetermined limit, and the expected duration is smaller than or the same as the handover latency, the handover is initiated.

In the second scenario, if the user drives to a wireless cell, handover is released if the mean RSS metrics of the WLAN signal are above a certain level and if the bandwidth available from the WLAN satisfies the application's requirements in terms of bandwidth.

Authors in [121] propose an algorithm between the wireless cell and 3G based on comparing the existing RSS and a dynamic RSS threshold whenever the user is linked to a WLAN access point. The RSS dynamic threshold provides a good solution as it decreases the impact of false handover triggers and maintains handover faults below the threshold.

To avoid useless handovers introduced in the previous method, an algorithm has been developed for estimating the covered distance [113], [133]. The algorithm takes into account the amount of time the user is supposed to stay in the cell. It is based on the travel time of the WLAN and the estimated travel time of the WLAN. A handover is started when there is available WLAN coverage and the expected travelling time in the WLAN cell is greater than the threshold value.

The primary feature of this method is to reduce data handover errors, useless handovers and failures in connection to the minimum, regardless of the longer handover time.

#### **4.5.2 VHO Algorithms based on bandwidth**

In such algorithms, the main criterion for handovers is the availability of bandwidth. An algorithm based on the quality of service is proposed [125], that includes the available residual bandwidth and the needs of the user in terms of service in order to decide to move from a wireless local area network (LAN) to a wireless wide area network (WWAN) and vice-versa.

If the mobile terminal is in the idle state, a handover to the preferred access network is performed; otherwise, the handover decision is based upon the user application type. This method is able to achieve high throughput as the available bandwidth is considered as the main criteria for VHD. Also by taking application types into account, lower handover latency for delay-sensitive applications is achieved.

To improve the overall system throughput, an algorithm is developed [124] between WLAN and Wideband Code Division Multiple Access (WCDMA), which takes into consideration the Signal to Interference and Noise Ratio (SINR). The SINR calculation of the WLAN signals is converted to an equivalent SINR to be compared with the SINR of the WCDMA channel.

SINR based handovers can provide users with higher overall throughput than RSS based handovers since the available throughput is directly dependent on the SINR, and this algorithm results in a balanced load between the WLAN and the WCDMA networks. However, these algorithms may also introduce a ping-pong effect.

To reduce the unnecessary handovers a Wrong Decision Probability (WDP) prediction based algorithm [123] is proposed. In this method, the probability of unnecessary and missing handovers is combined and WDP is calculated. This algorithm is able to reduce the WDP and balance the traffic load.

#### **4.5.3 VHO Algorithms based on Cost Function**

The basic idea of a cost function based vertical handoff decision algorithm is to choose a combination of network and factors such as RSS, a network coverage area, available bandwidth, service cost, reliability, security, battery power and mobility model. A cost function is defined based on these factors to evaluate the performance of target networks. The handover decision can then be made accordingly.

There is an algorithm based on multiservice [134], which is based on a cost feature that computes the cost of each possible target network and ranks all the applications according to their priority. This method has the advantages of using the cost function, as well as increasing the percentage of requests served by users and reducing the probability of blocking.

A handover decision algorithm based on the cost function with normalization and weight distribution is proposed, where the methods used are provided [135]. The quality of the network factor has been applied to evaluate the performance of a handover target candidate. This method leads to a high throughput system and user satisfaction.

An algorithm based on a weighted function [128] that assigns the computation of VHO to the visited network rather than to the user is used. The candidate network having the most weighted function is chosen as the target network for handover. The benefit of this approach is that the handover decision time is decreased, the handover blocking rate is low and the data rate is high.

#### **4.5.4 VHO Algorithms based on Multiple Attributes Decision Making**

The multiple attributes decision-making based algorithm (MADMA) [136] calculates the quantitative value of each normalized attribute and evaluates the target systems through the weighted function of the quantitative values. The final decision can then be made.

In the Simple Additive Weighting (SAW) based MADM system, various factors have been assigned with different weights that can be adapted dynamically depending on the state of the network and the different user services; it is, therefore, feasible to ensure different QoS demands on users and to enhance the performance of the entire network.

The Grey Relationship Analysis Algorithm (GRAA) is an analytical method that measures the level of correlation of factors according to the degree of similarity and variation of the factors shown by the Grey Relationship Coefficient (GRC). GRAA is used to compute the degree of correlation of every candidate network with the user's actual network. GRC can also be merged with alternative techniques such as Fuzzy Logic to enhance the performance of the Vertical Handover Algorithm.

The GRAA can analyse several elements of the system with little data and the tendency of the system development may be quantified accordingly. The GRAA is, therefore, very well adapted to dynamic network analysis; however, the complexity involved in the calculations is high, thus reducing its utility application in practice.

#### **4.5.5 Combination Algorithm**

Combining algorithms bring together different parameters in handover decision, similar to those used in cost function algorithms. These algorithms use artificial neural networks or Fuzzy Logic.

VHO algorithm is developed using Artificial Neural Networks (ANNs) [119]. The mobile device receives the characteristics of the available wireless networks and transmits them via the available links. There are three major components of the Vertical Transfer Manager: the network management manager, the featured collector and the training/selection of the ANN. A multi-layered ANN is used to determine the best available transfer target wireless network for the user's device, based on the user's preferences.

The Fuzzy Logic technique allows overcoming the problem of vertical handover using fuzzy parameters. This type of algorithm processes a wide range of input parameters to make a vertical handover decision. An algorithm based on Fuzzy Logic [137] is implemented to handle handovers between WLAN and UMTS. A predetermined decision unit is applied in this method. This algorithm is capable of enhancing performance by decreasing the number of useless handovers and preventing the ping-pong effect.

#### **4.5.6 Authentication Based Algorithms**

In next-generation networks, safety is seen as one of the most critical issues to be addressed in mobile networks. The mobility of users raises the danger of illegal users acting as legal users. It is, therefore, necessary that the handover process ensures security as well as an authentication system. It must also allow the authentication time during the handover process to be reduced.

An authentication scheme for rapid handover among WI-Fi access points is provided [138], where schemes are designed to reduce the authentication delay during a WiFi handover process. This system makes effective use of pre-authorization and removes the requirement to communicate with the remote server when the handover occurs. This system is able to minimize the authentication latency, and the linear dependency on Round Trip Delay between the AP and the authentication server is also removed.

## 4.6 Analysis of VHO algorithm

Table 4.1: Analysis of VHO algorithms [113]

Algorithms		Parameter
<b>RSS based</b>	Adaptive Lifetime based	RSS
	RSS threshold Based	RSS with threshold
	Travelling Distance Prediction Based	Dynamic Time threshold
<b>Bandwidth Based</b>	QoS Based	Residual Bandwidth and service requirements
	SINR based	Signal to Noise Interference Ratio
	WDP Based	Probability of Unnecessary and missing handovers
<b>Cost Function Based</b>	Multiservice	Cost of target network
	Cost function with Normalization and weights distribution	Network Quality factor
	Weighted Function Based	Weighted function of network
<b>MADMA</b>	Simple Additive Weighting	Bandwidth, jitter, delay, packet loss
	GRA	Bandwidth, Jitter, Delay, Cost
<b>Combination</b>	Multilayer feed forward	Cost
	Fuzzy Logic based	RSS, Bandwidth
<b>Authentication</b>	Authentication scheme between Wi-Fi access points	EAP-SIM protocol

Starting with the RSS algorithms, the adaptive lifetime is introduced and combined with the estimated lifetime to decide the handover time. This technique improves the available bandwidth but the packet transmission time is high. The second technique is RSS with a threshold where a dynamic RSS threshold is calculated and compared to the current RSS to determine the handover time. The dynamic RSS threshold reduces the probability of HO failure but increases network resource waste. The third technique in the RSS algorithms is the Travelling Distance Prediction where a dynamic times threshold is calculated and compared with the predicted travelling time to determine the handover. This technique reduces the number of unnecessary HO but needs an extra HO delay.

The second algorithm is based on bandwidth. To begin with, the QoS is based on residual bandwidth and service requirements where bandwidth is combined with RSS, system requirements

and application type to make the handover decisions. This technique guarantees low HO latency and a high throughput system but increases the blocking rate of a new application. The second technique is based on the Signal-to-Noise Interference Ratio. This technique provides high throughput and balanced load but allows excessive handovers and a ping-pong effect. The third technique is based on Wrong Decision Probability (WDP) where the available bandwidth, network coverage and probability of missing handovers are considered to determine handover. This method reduces WDP and provides a balance of traffic load but increases the connection breakdown.

The third algorithm is based on a cost function. This technique is a multiservice one based on the cost of the target network. The cost of the possible target network is calculated and the network with the minimum cost function is selected. This technique increases user satisfaction and reduces the blocking probability. The second technique is the cost function with normalization and weights distribution that provide a high system throughput and ensure high user's satisfaction, but it is difficult to estimate parameters like security and interference level. The last technique in this algorithm is the weighted function where the resource of the mobile can be saved. A low handover delay and a low blocking rate can be provided with high throughput, but it requires extra coordination between MT and the point of attachment.

The fourth algorithm is the multiple attributes of the decision-making algorithm. The first technique is the simple additive weighting where the score of each candidate network is determined by the weighted sum of all the attribute values. This technique reduces the processing delay with a lesser number of parameters. The second technique is the Gray Relation Analysis (GRA) which is based on bandwidth, jitter, delay and cost which reduces the procession delay. However, the handover dropping rate using GRA is high.

The fifth algorithm is the combination algorithm. The first technique is the multilayer feed-forward based on artificial neural networks (ANN) where the cost function is used to train ANN. This technique helps to find the best available network, but it takes a long time during the training process. The second technique is Fuzzy Logic that is based on RSS bandwidth. This technique reduces the number of unnecessary handovers and avoids the ping-pong effect.

The last algorithm is the authentication scheme between Wi-Fi access points where Pre-authorization is used to eliminate the need for communication with the remote server at the time of handover. This technique reduces the authentication delay, but it is proposed for Wi-Fi access points only.

## 4.7 VHO algorithm for the VLC

Authors in [139] introduce a new VHO algorithm from VLC to LTE through a prediction called PVHO. This algorithm addresses the variability of some critical parameters that depend on vehicles traffic and network situations. PVHO can be used as an effective method to guarantee the quality of service of the VLC network. However, the PVHO do not consider the situation where LTE is unavailable and where another RF technology is required.

In [140], the authors present an indoor hybrid system that combines WiFi and VLC fixtures. This system uses broadcast VLC channels to support RF communications and a handover mechanism between WiFi and VLC to deliver resources dynamically and to maximize the data rate. This approach brings benefits of VLC throughput, provides compatible connectivity with existing RF devices, and shows excellent scalability. Authors in [141] study horizontal Handover instead of VHO, where the proposed mechanism permits a switch between two independent VLC links; in other words, a homogeneous system and not a heterogeneous one.

A survey on the performance of indoor VLC-WLAN access point networks in a wireless scenario is completed in [142]. The authors present the VHO method without setting out clear steps, which appears to be a simplified process. In addition, many authors [143]–[146] have worked on fuzzy logic that is considered a technique for handling imprecise data. Furthermore, [147] have proved that fuzzy logic is an ideal tool for dealing with uncertain cases. For example, an advanced VHO algorithm based on Fuzzy Logic is developed in [145] to overcome the problem of blocking the LOS communication link for the RF-Infra-Red (IR) communication system. The proposal here is based on a pre-training procedure. In addition to the fact that the suggestion also applies to indoor VLC systems, the algorithm identifies the need to set a fixed waiting time before making handover, regardless of the efficiency of this waiting time on system performance. An inappropriately allocated delay may result in a higher system latency, which is the main requirement to be minimized in safety-based ITS applications.

The authors in [148] apply VLC technology to achieve high accuracy location of a vehicle based on a positioning technique using existing vehicle lighting to deliver amplitude-modulated tones. These tones can be treated to obtain the arrival phase difference, which can be transformed into distance differences. Well-known positioning equations can then be applied. The authors do not consider a real scenario where the transmitted messages may be affected by interfering vehicles.

The research in [66] focuses on the use of VLC in ITS application by providing the traffic flow information from traffic lights to vehicles, where a service area is designed and evaluated. Its performance is affected by the receiver's position, the angle, the field of view, and the receiver's vertical inclination. The authors work on the simplest scenarios; however, they should have worked on a situation more complex (no heavy vehicle running ahead). The authors in [68] use the NS2 network simulator to demonstrate the VLC-based system that can meet the high requirements of accessibility for V2V communication in heavy vehicle traffic conditions. Their experiments demonstrate that the angle of view from a receiver makes the VLC resistant to visible sunlight noise. They take advantage of the multiple paths available to reach the vehicles and overcome the effects of packet collisions, but they do not work on the worst-case scenario if there is no path available anymore.

## 4.8 Conclusion

In this chapter, we studied the vertical handover that permits the switch from one network technology to another technology by taking into consideration different criteria. First of all, we started by making an overview of the essential handover phases: initiation phase, network selection phase, execution phase.

Then the different handover types were introduced: the horizontal handover and the vertical handover. HHO is defined by the switch from one base station to another one for the same technology and VHO is defined by the switch from one network to another. The handover decision is done based on some parameters: receiver signal strength, network connection time, handover latency, available bandwidth and power consumption.

The VHO algorithms are classified according to different techniques. These algorithms are divided into six different categories: receiver signal strength algorithms, Bandwidth algorithms, Cost function algorithms, Combination algorithms, Multiple Attributes Decision Making Based Algorithms and Authentication Based Algorithms.

The improvements in the communication system have resulted in an enhancement of the level of quality of service delivered by the different radio access technologies. In a heterogeneous environment, obtaining access to these different technologies demands an efficient handover process. To meet these requirements, it is necessary to develop a VHO algorithm that should be efficient and effective in terms of evaluation criteria.

# 5. Chapter 5: Speed Platoon Splitting SPS

## 5.1 Introduction

Vehicular network issues (network stability and congestion) have increased the need to create a new vehicle algorithm which is the platoon. Platoon is considered as a very appropriate solution for vehicular issues as well as an appropriate technique that can be used to study the mobility and quality of service that is one of our contributions.

Grouping of autonomous vehicles (platooning) offers the opportunity to improve road safety, increase traffic efficiency and decrease fuel consumption. The main purpose of platoon control is to ensure that all vehicles in a group are travelling at a common speed and at the same time keeping the desired gaps between all adjacent vehicles.

In this chapter, we will develop and evaluate a new platoon formation algorithm called speed platoon splitting for organizing vehicles into platoons at the entrances ramp to deal with the gaps of the preceding platoon formation algorithms reviewed in chapter three (congestion problem, platoon splitting.. ). SPS contributions are:

- SPS maximizing platoon lifetime by choosing the leader vehicle that has the farthest destination and the last vehicle which has the nearest destination.
- It regulates vehicular flow by controlling inter-platoon spacing through the ticket pool mechanism that regularly generates admission tickets.
- SPS considers two types of lanes according to the chosen velocity: high-speed platoon and low-speed platoon. This velocity classification helps to better satisfy the driver's requirements in terms of speed.
- Communication between vehicles to avoid accident risks using RF technology or/and Visible light communication.

In this chapter, we present an overview of the new platoon formation algorithm called speed platoon splitting in section 5.2. We focus on the simulation scenario and the simulation parameters in section 5.3. In Section 5.4, we evaluate the performance results and the analysis before concluding the chapter in section 5.5.



## 5.2 SPS algorithm

### 5.2.1 SPS algorithm description

SPS algorithm takes into account 2 important parameters that affect the performance of our algorithm.

#### 5.2.1.1 Velocity

Vehicles have different speeds on a highway: some vehicles move at a high speed and others at a low speed. Platoon constrains high-speed vehicles to slow down to the velocity of the head. Conversely, vehicles with low speed will be obligated to speed up in order to stay in a platoon having a head moving at a high speed. Therefore, the SPS algorithm takes into account the velocity. We worked on 2 different lanes where each vehicle chooses the appropriate lane according to its velocity.

#### 5.2.1.2 Traffic congestion

Platoon formation algorithms in the literature do not take vehicular density and congestion into consideration. Indeed, traffic congestion occurs when vehicular density exceeds highway capacity.

Traffic congestion has several negative effects [149]:

- Wasting time for motorists and passengers ("opportunity cost"). As a non-productive activity for most people, congestion reduces regional economic health.
- Delays may result in late arrival for employment, meetings, and education, resulting in business loss, disciplinary action or other personal losses.
- Stressed and frustrated motorists, encouraging road rage and reduced health of motorists.
- Emergencies: blocked traffic may interfere with the passage of emergency vehicles travelling to their destinations where they are urgently needed.
- Higher chance of collisions due to tight spacing and constant stopping-and-moving.

To avoid these negative effects, we apply an algorithm that limits the number of vehicles on the highway.

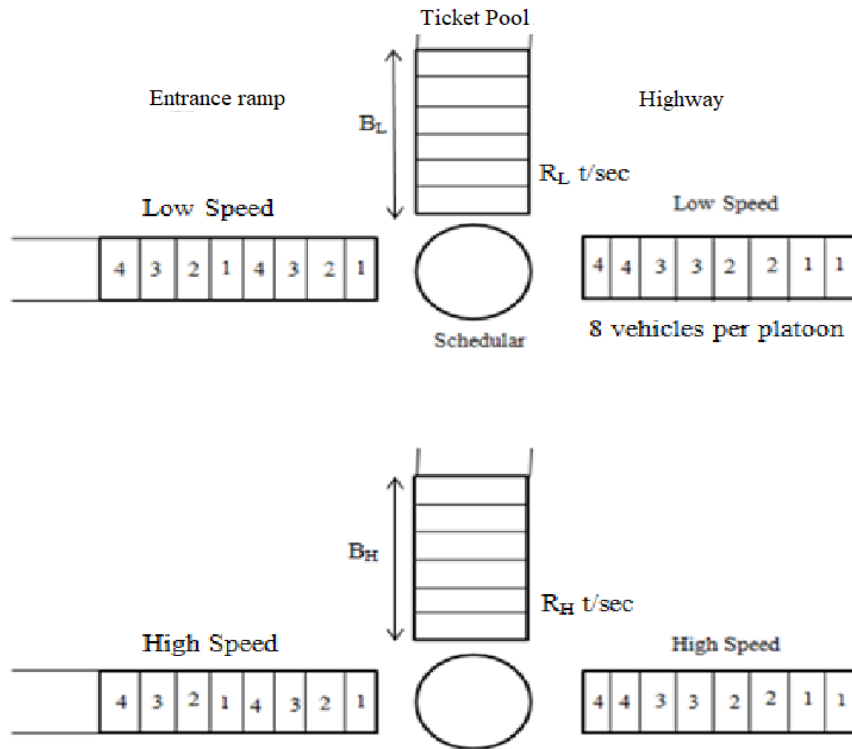


Figure 5.1: SPS algorithm

In our new algorithm (see Figure 5.1), we consider that each highway entrance is equipped with a ticket pool that controls the volume of vehicle traffic entering the road by applying preventive congestion control.

The congestion control mechanism consists of two waiting queues with finite capacities,  $K_1$  and  $K_2$  that accommodate vehicles with high velocity and low velocity respectively. Vehicles arriving in a bursting pattern are first queued in the corresponding waiting queue.

At highway entrance, the ticket pool has finite capacity  $B$  where tickets are generated with a rate  $R$  (at each ticket generation time  $T=1/R$ ) and stored in the pool. Each platoon should acquire a ticket to be accepted on the highway, and the ticket following an acceptance is removed from the ticket pool. The ticket pool controls vehicle traffic and prevents congestion.

The working mode of SPS algorithm description:

- Vehicles on the entrance ramp are divided into two lanes: one lane for low-speed vehicles and the other for high-speed vehicles. This allows the vehicle to choose the appropriate speed.
- The high-speed vehicle pool has a  $B_H$  capacity and generates  $R_H$  tickets per second; on the other hand, the low-speed vehicle pool has a  $B_L$  capacity and generates  $R_L$  tickets per second to control the generation of platoons on the highway.
- Each lane is controlled by a scheduler and a ticket park that indicates the time it takes for a platoon to get to the highway.
- On each lane, the vehicles on the access ramp are classified so that the lead vehicle has the furthest destination and so on to ensure the stability of the platoon.
- When a group of vehicles (8 or fewer vehicles) acquires a ticket, it joins the highway.

The flowchart of the SPS algorithm can be shown in (Figure 5.2) and (Figure 5.3) below:

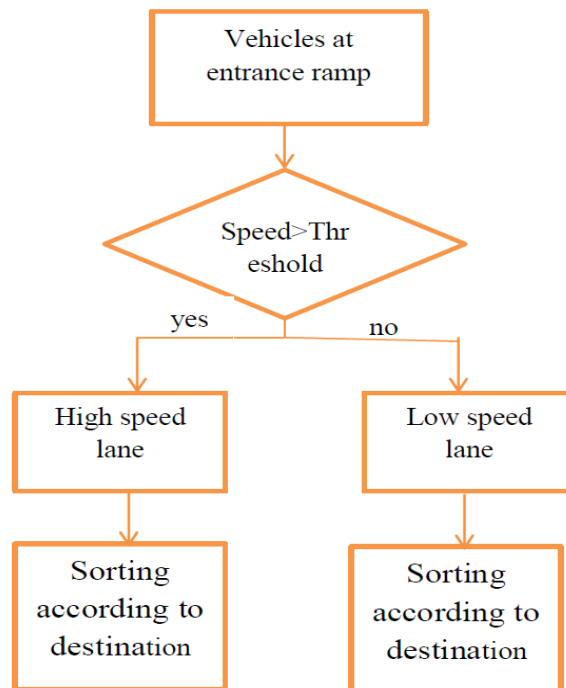


Figure 5.2: Flowchart of SPS algorithm for vehicles at the entrance ramp

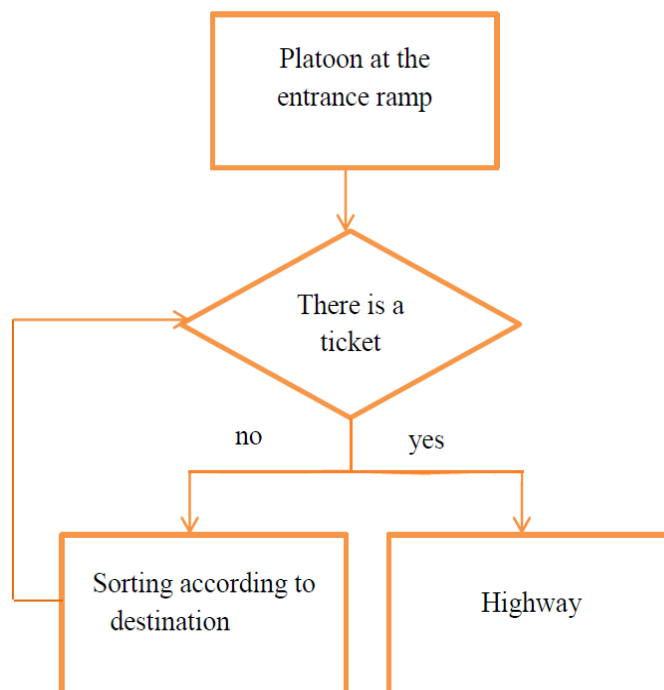


Figure 5.3: Flowchart of SPS algorithm at the entrance ramp

## 5.3 Simulation

In this section, we evaluate the performance of the Speed Platoon Splitting (SPS) algorithm detailed in the previous section. We start by highlighting the simulation scenario and simulation parameters. Afterwards, we exhibit performance results and provide a performance analysis.

### 5.3.1 Simulation scenario

Our architecture is composed of two principal lanes: the first lane is for high-speed vehicles and the second lane for low-speed vehicles. In each lane, platoons of vehicles with the same speed circulate. The entire platoon moves depending on the Krauß model. Krauß is a car-following model that can effectively describe the strong interaction among adjacent vehicles with close spacing. The general diagram of a car-following model is illustrated in (Figure 5.4).

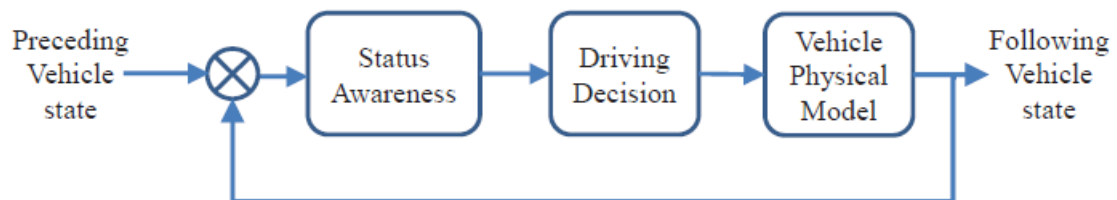


Figure 5.4: General scheme of the car following models [150]

At the end of the entrance ramp, there is a ticket pool. The platoon leader must acquire a ticket to move to the highway. At the end of the highway, vehicles in each lane must circulate to cross one of the exits.

### 5.3.2 Simulation parameters

Different parameters are taken into consideration:

- Lanes: 2 different lanes, one for high speed (80 km/h-100km/h) and the other for low speed (40km/h-60km/h)
- Arrival: The arrival of vehicles at the entrance ramp is Poisson arriving mode. (200 vehicle/h-2000 vehicle/h)
- Ticket pool: 2 ticket pools between the entrance ramp and the highway, one for high-speed lane and the other for low-speed lane. Each platoon should acquire a ticket to be accepted on the highway, and the ticket following an acceptance is removed from the ticket pool
- $l$ : number of lanes on the highway
- $L_{high}$ : highway length
- $L_{car}$ : length of the car
- $SD$  minimum safety distance
- Distance: 100 km
- Platoon length: The maximum platoon length is 8 vehicles/platoon
- Exits: There are 4 destinations at the end of the highway

- Ticket pools parameters:
  - Finite capacity  $M$  tickets
  - Tickets are generated at a constant rate
  - Ticket generation time  $T=1/R$

### 5.3.3 Performance parameters

To evaluate our algorithm, we computed the following performance parameters for SPS algorithm:

- Platoon lifetime: it measures the time elapsed before splitting the platoon
- Number of platoons: it computes the number of platoons on the highway

To compare SPS algorithm with DGPS algorithm, we have completed a set of performance parameters for both DGPS and SPS algorithms for different velocities:

- Platoon communication percentage loss: It describes the ratio between the lifetime  $T_1$  that the vehicle spends staying alone out of the platoon until it reaches its destination and the lifetime  $T$  of the platoon. When there is congestion,  $T_1$  increases so the platoon communication percentage loss increases.
- Distance between platoons: It describes the distance between two platoons. This distance decreases in case of congestion and increases when the congestion is alleviated.
- Trip time: it computes the time needed for a vehicle before leaving the platoon and reaching its destination.
- Waiting time at the entrance ramp: it is equal to the time that a vehicle waits in the platoon before entering the highway.

## 5.4 Performance results and analysis

This section exhibits the performance results of the platoon formation algorithm. We start by evaluating SPS algorithm with different speeds and the number of platoons on the highway. Afterwards, we shed light on the performance study of SPS and DGPS.

Figure 5.5 illustrates the average lifetime of a platoon in the function of flow rates for different velocities.

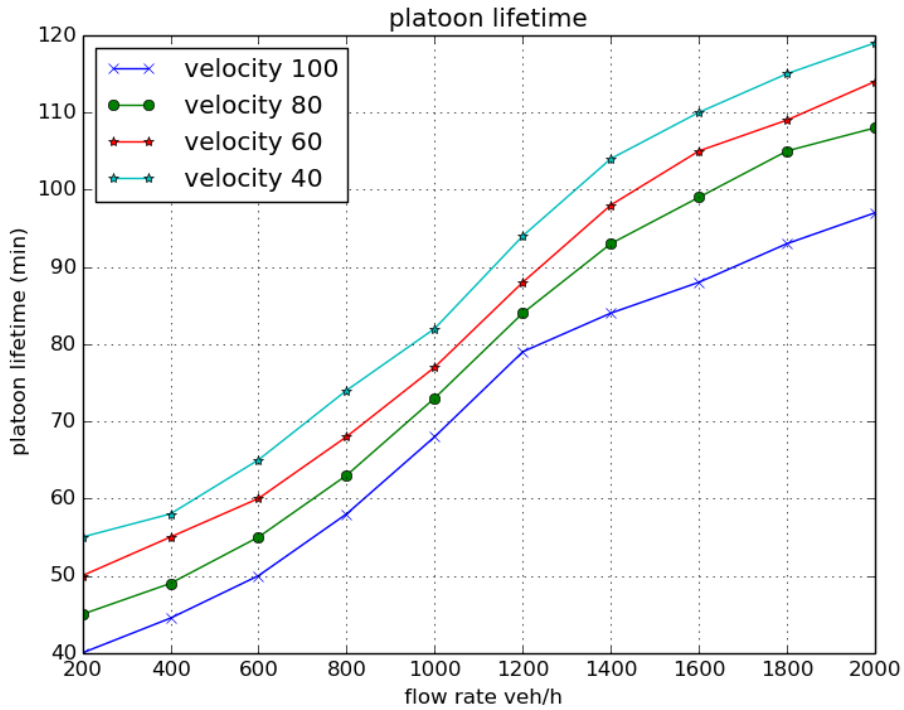


Figure 5.5: Lifetime of the platoon for SPS with different speeds

We notice that when the flow rate increases, the average lifetime of the platoon increases. That is, when the congestion increases, the platoon needs more time to be split up. For a constant flow rate, when the velocity increases, the average lifetime of the platoon decreases. That is, when the velocity becomes higher, the platoon takes less time to cross the highway. Therefore, its lifetime decreases.

Figure 5.6 depicts the average number of platoons in the function of flow rate for vehicles driving at high speed and for those driving at low speed.

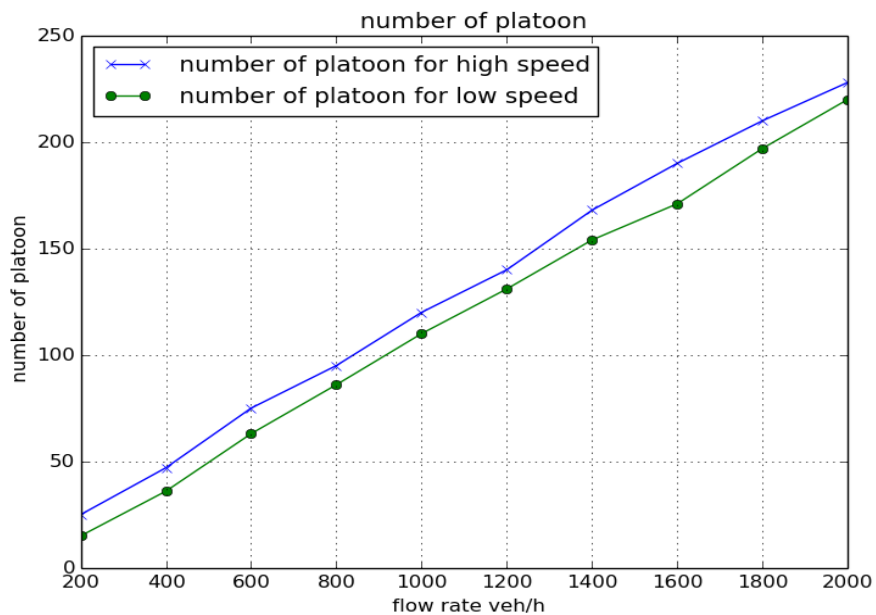


Figure 5.6: Number of platoon for SPS

We notice that when the flow rate increases, the number of platoons increases. Indeed, when the flow rate increases, the number of vehicles on the highway increases. Therefore, the number of platoons increases. We suppose that the time needed for the generation of the ticket at high speed is less than at low speed. Therefore, there are more platoons with a high speed than those of low speed.

Figure 5.7 illustrates the loss percentage in function of flow rate for DGPS and for SPS algorithms with different velocities.

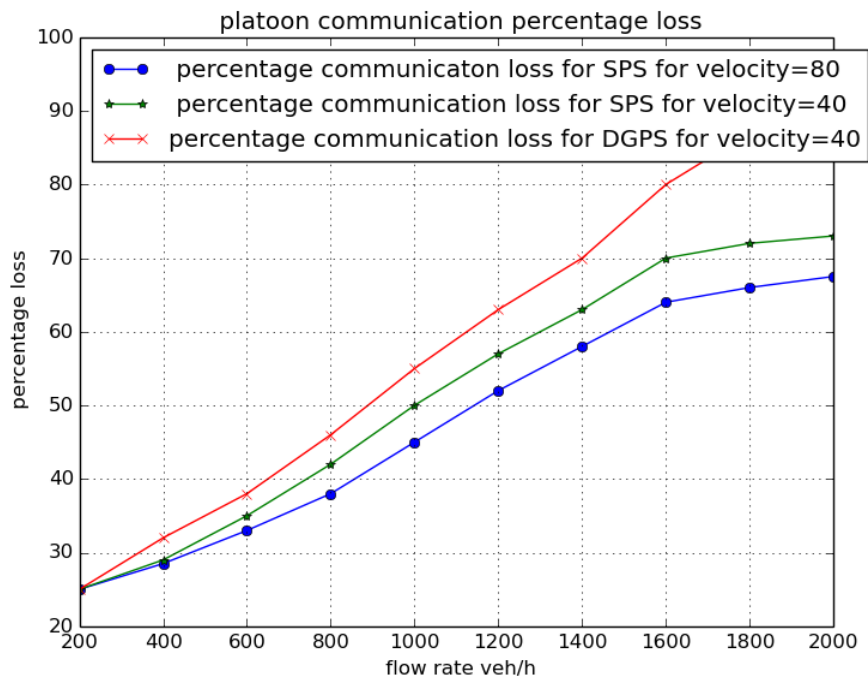


Figure 5.7: Platoon communication percentage loss

We notice that when the flow rate increases, the loss percentage increases. That is, when the number of vehicles increases on the highway, the time that the vehicle stays alone increases as the congestion increases. For a constant flow rate, we notice that the loss percentage for DGPS is higher than that of SPS. That is simply because with SPS algorithm, there is less congestion than with DGPS algorithm. In fact, with SPS algorithm, there is a ticket pool which alleviates congestion. As the congestion is alleviated, the time needed for a vehicle to stay alone is reduced; therefore, the loss percentage is reduced.

Figure 5.8 depicts the distance between platoons in function of flow rate for DGPS and SPS algorithms.

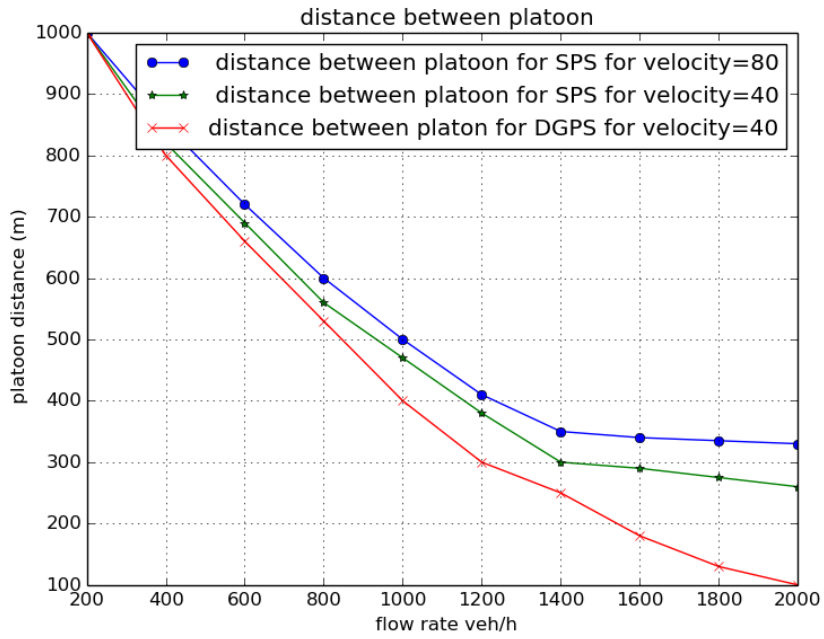


Figure 5.8: Distance between platoons for SPS and DGPS

We notice that the distance between platoons decreases when the flow rate increases. This is due to the congestion that occurs at high rates. For a constant flow rate, we notice that the distance between platoons is lower when there is congestion. That justifies that this distance is higher for SPS algorithm than that of DGPS algorithm.

Figure 5.9 spots the platoon lifetime in function of flow rate for DGPS and SPS algorithms.

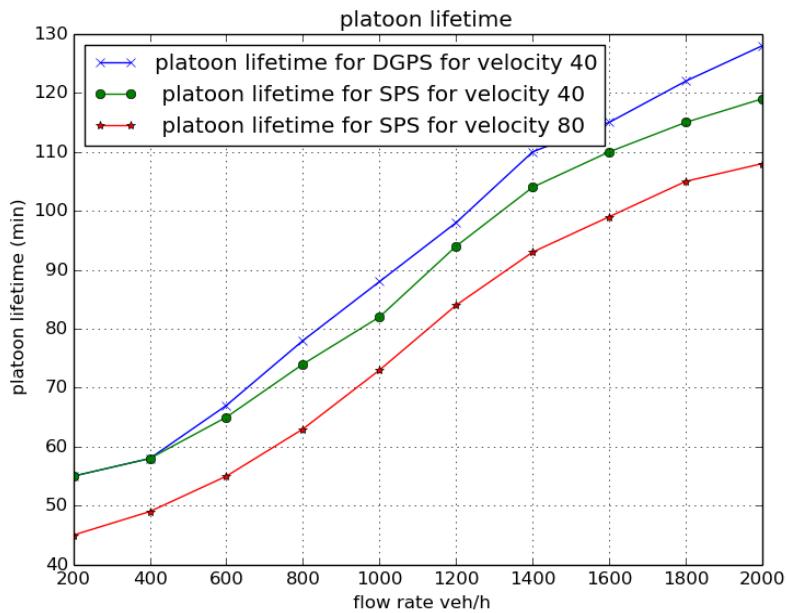


Figure 5.9: Platoon lifetime for SPS and DGPS



We notice that the platoon life increases when the flow rate increases. That is, the platoon takes more time staying intact when the congestion increases. For a constant flow rate, the platoon lifetime is lower for the algorithm that alleviates congestion. This justifies that platoon lifetime is lower for SPS algorithm.

Figure 5.10 illustrates the trip time of the vehicle in the platoon in function of flow rate for DGPS and SPS algorithms.

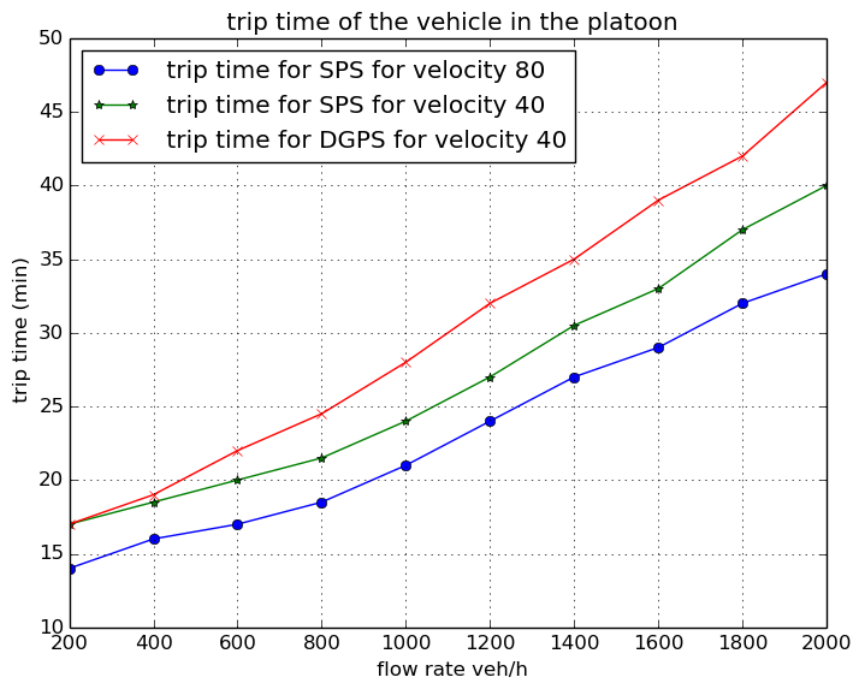


Figure 5.10: Trip lifetime for SPS and DGPS

We notice that the trip time of the vehicle in the platoon increases when the flow rate increases. That is, the vehicle takes more time staying in the platoon when the congestion increases. For a constant flow rate, the trip time is lower for the algorithm that alleviates congestion. That is, the trip time is lower for SPS algorithm.

Figure 5.11 depicts the waiting time in the entrance ramp in function of flow rate for DGPS and SPS algorithms.

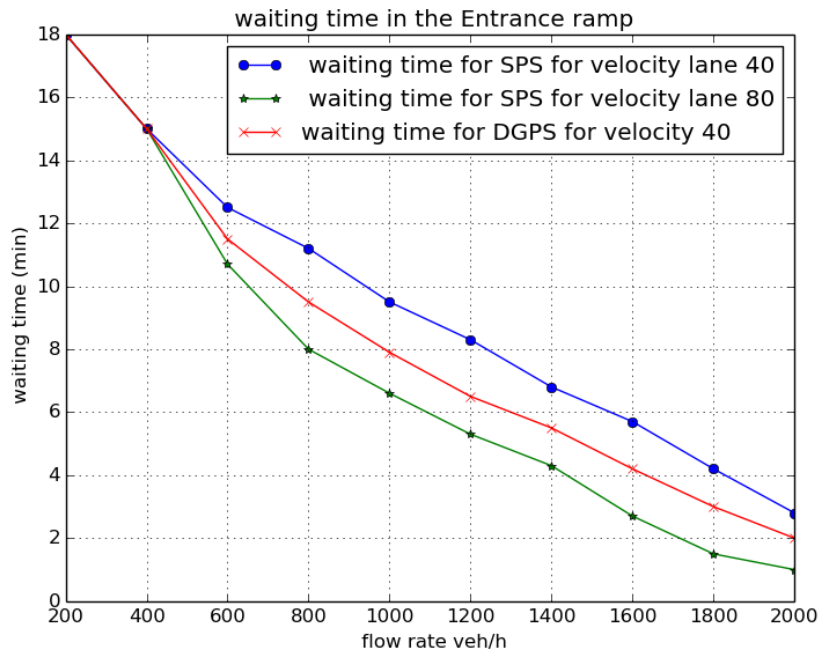


Figure 5.11: Waiting time for SPS and DGPS

We notice that when the flow rate increases, the congestion increases. The platoon is completed more quickly, and the waiting time decreases. For a constant flow rate, vehicles with SPS algorithm wait for a ticket to be moved to the highway. Therefore, the waiting time is higher than that of the DGPS algorithm.

## 5.5 Conclusion

Platooning is a new concept that enables vehicles to be grouped together so that they exchange road safety messages. Vehicular platooning helps in improving traffic flow performances in transportation systems. The main idea is that the throughput of vehicles on freeways may potentially increase by forming vehicle platoons with small intervehicle spacings, which allows more vehicles to fit on a road segment.

In this chapter, we propose an innovative platoon formation algorithm SPS that considers vehicular congestion and vehicles velocity. At the entrance ramp, SPS adopts a ticket pool mechanism that achieves vehicular flow regulation.

After evaluating the performance of the SPS algorithm, we notice that SPS saves up drivers' time; therefore, it overcomes DGPS and all other strategies proposed in the literature. Moreover, SPS decreases communication loss percentage of vehicles, the platoon lifetime and the vehicle lifetime in the platoon.

## 6. Chapter 6: VLC performance

### 6.1 Introduction

The majority of research papers achieve a performance study and mathematical models without taking into account the impact of interference caused by perturbing vehicles.

Our research study focuses on studying the impact of vehicular perturbation on VLC performance parameters. More specifically, our contributions in this chapter are:

- We provide two case studies
- We provide two mathematical models that evaluate the performance of a platoon of cars in the presence of disruptive vehicles in real case scenarios.
- Two mathematical results are validated by two accurate simulations.

This chapter is organized as follows: section two presents the first scenario that will be discussed. In this section, we highlight the mathematical model as well as the performance parameters and illustrate the vehicle section performance results obtained by simulation and mathematical modelling. Section three provides a real scenario with a mathematical model and performance parameters which are introduced in this section. This section shows the performance results of this real scenario before concluding this chapter.

### 6.2 Case study 1

Our first case study emphasizes the performance evaluation of the VLC in a vehicular platoon. We consider a highway consisting of two lanes (Figure 6.1):

- The right lane is reserved for platoons. Every vehicle in the platoon travels using a car following mobility model (Krauß).
- The left lane is reserved for disruptive vehicles that travel at a speed of 100 km/h. These vehicles interfere with the platoon vehicles.

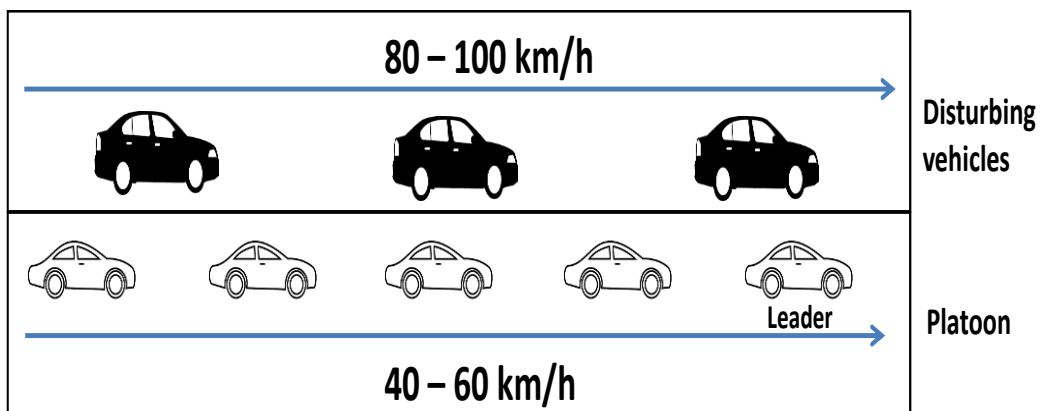


Figure 6.1: VLC scenario

Furthermore, we assume a non-preemptive priority model. This model is active when we already have a packet in the channel transmitted between the vehicles' platoon, and disruptive vehicles arriving at the same time to disturb the channel using their light. This packet is received successfully since we are using a non-preemptive priority because interference time (sec) is much greater than packet transmission time (msec). However, the following packets transmitted by the vehicles' platoon are blocked until all disruptive vehicles stop their transmission and overtake the platoon.

### 6.2.1 Performance evaluation

In this section, we conduct mathematical modelling in order to evaluate the performance of visible light communication in the presence of disruptive vehicles.

#### 6.2.1.1 Mathematical model M/M/1

Our study case is modelled with a multi-class non-preemptive priority model (Figure 6.2):

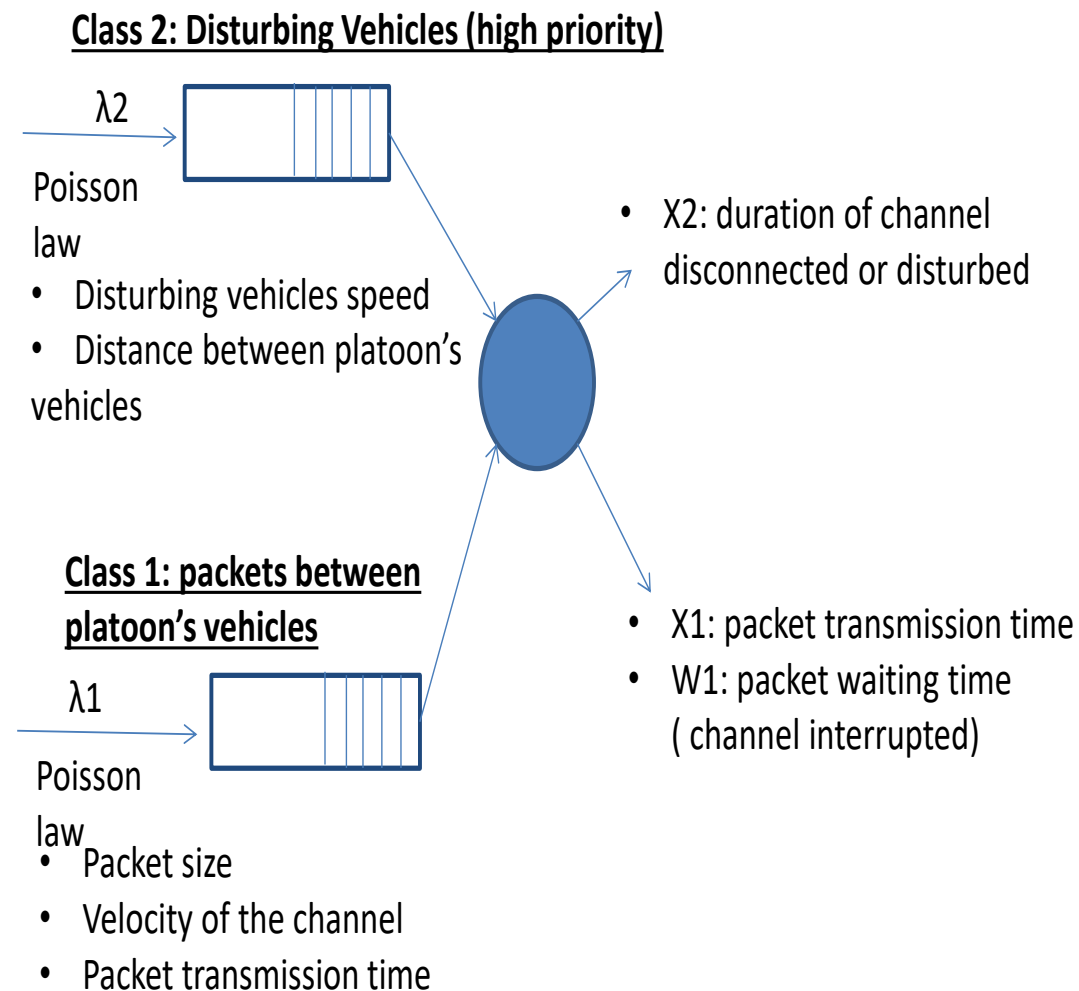


Figure 6.2: Priority model

- Class 1 represents packets generated by vehicles platoon: Arrival rate of packets follow the Poisson arrival rate with a mean rate  $\lambda_1$ .
- Class 2 represents disruptive vehicles: The arrival rate of disruptive vehicles follows the Poisson arrival rate with a mean rate  $\lambda_2$ .

We assume that class 2 presents a higher non-preemptive priority over class 1. Furthermore, we consider the following parameters:

- The mean packet length is  $L$ .
- The mean packet transmission time is  $T_1$ .
- Mean packet waiting time,  $T_w$  is the activity period of disruptive vehicles
- The mean channel speed is  $\mu_1$ .
- The period of the first disruptive vehicles is  $X_2$ .
- The period of the following disruptive vehicle is  $\varphi$

### 6.2.1.2 Performance parameters

In order to evaluate the performance of VLC scenario, we computed the following performance parameters:

#### A. Probability of failure

The Poisson arrival rate is considered a simple metering system with independent and stationary increments where the probability of success is equal to:

$$Prob\ of\ success = \frac{(\lambda \times t)^K}{K!} \times e^{-\lambda \times t} \quad (1)$$

In order to successfully receive packets, we should not have disruptive vehicles ( $K=0$ ) on the highway ( $\lambda = \lambda_2$ ) during the period  $T_1$  ( $t=T_1$ ).

$$Prob\ of\ success = \frac{(\lambda_2 \times T_1)^K}{K!} \times e^{-\lambda_2 \times T_1} \quad (2)$$

$$K = 0 \text{ (0 perturbation vehicles during } T_1) \quad (3)$$

$$Prob\ of\ success = e^{-\lambda_2 \times T_1} \quad (4)$$

$$Prob\ of\ failure = 1 - Prob\ of\ success \quad (5)$$

$$Prob\ of\ failure = 1 - \frac{(\lambda_2 \times T_1)^K}{K!} \times e^{-\lambda_2 \times T_1} \quad (6)$$

$$Prob\ of\ failure = 1 - e^{-\lambda_2 \times T_1} \quad (7)$$

### B. Usable throughput

The usable throughput is applied for  $K=0$ , where no interfering vehicles are present on the highway and messages are well received. The usable throughput is equal to the number of packets sent during a period  $T1$

*Usable throughput = number of packets during  $T1$   $\times$  Prob of success*

$$\text{number of packets during } T1 = \frac{\lambda_1 \times T1 \times L}{T1 + Tw} \quad (8)$$

The usable throughput  $S$  is:

$$S = \frac{\lambda_1 \times T1 \times L \times \text{Prob of success}}{T1 + Tw} \quad (9)$$

$$\text{Prob of success} = e^{-\lambda_2 \times T1} \quad (10)$$

$$S = \frac{\lambda_1 \times L \times T1 \times e^{(-\lambda_2 \times T1)}}{T1 + Tw} \quad (11)$$

### C. Activity period of the disruptive vehicle (high priority):

The activity period of the disruptive vehicles is the period in which no packets can be sent because the channel between vehicles is disturbed. This period is composed of consecutive perturbation where the period of the first disruptive vehicle is  $X_2$  and  $\phi_k$  is the period of the followed vehicles.

$$Tw = X_2 + \sum_{i=1}^k \phi_k \quad (12)$$

### D. Virtual service time of a non-preemptive packet (VST1)

It defines the activity period of the lower priority class that is composed of the waiting time and the service time

The virtual service time VST1 of packets is composed of:

- $T1$  if we do not have disruptive vehicles that interfere with the communication between vehicles' platoon on the highway (queue 2 is inactive)
- $Tw + T1$  if we have disturbing vehicles on the highway and we cannot send packets between vehicles' platoon because the channel is disturbed (queue 2 is active)

The probability of queue 2 active is  $\phi_2$  that is the coefficient rate of disturbing vehicles:

$$VST1 = T1 \times \text{prob of queue 2 inactive} + (Tw + T1) \times \text{prob of queue 2 active}$$

$$VST1 = T1 \times (1 - \phi_2) + (Tw + T1) \times \phi_2 \quad (13)$$

$$VST1 = T1 + Tw \times \phi_2 \quad (14)$$

$$\phi_2 = \frac{\lambda_2}{\mu_2} \quad (15)$$

E. Probability of K consecutive disturbances followed by success

It refers to the probability of K consecutive disturbances followed by a packet transmission process.

$$\text{Probability of K failure followed by success} = \text{Prob of K failure} \times \text{Prob of success} = (1 - e^{-\lambda_2 \times T_1})^k \times e^{-\lambda_2 \times T_1} \quad (16)$$

$k$ : Number of consecutive failures

$$\text{Prob of K failure} = e^{-\lambda_2 \times T_1} \times (1 - e^{-\lambda_2 \times T_1})^k \quad (17)$$

### 6.2.1.3 Simulation parameters

A. Simulation

To validate our mathematical model, we conducted a series of simulations performed using SUMO [151] and OMNET [152]. We considered an authentic car-following mobility model that captures the dynamics of vehicles equations (krauß)

B. Assumptions for simulation

Table 6.1: The parameters adopted for simulation

<b>Packet arrival rate <math>\lambda_1</math></b>	1000 packets/h
<b>Disruptive vehicle arrival rate <math>\lambda_2</math></b>	0 – 300 veh/min
<b>Packet size L</b>	1024 bytes
<b>Channel speed <math>\mu_1</math></b>	250 – 350 kbps
<b>Transmission time T1</b>	$T_1 = \frac{L}{\mu_1} = 0.03 \text{ s}$

## 6.2.2 Performance results

Highway congestion caused by a high arrival rate of interfering vehicles will affect the VLC's performance. To solve this problem, controlling disruptive vehicles is one of the options. The following figures illustrate the performance evaluated by mathematical models and simulations.

Figure 6.3 illustrates the usable throughput of the simulation model, the mathematical model in function of the arrival rate of disruptive vehicles  $\lambda_2$  (veh/min).

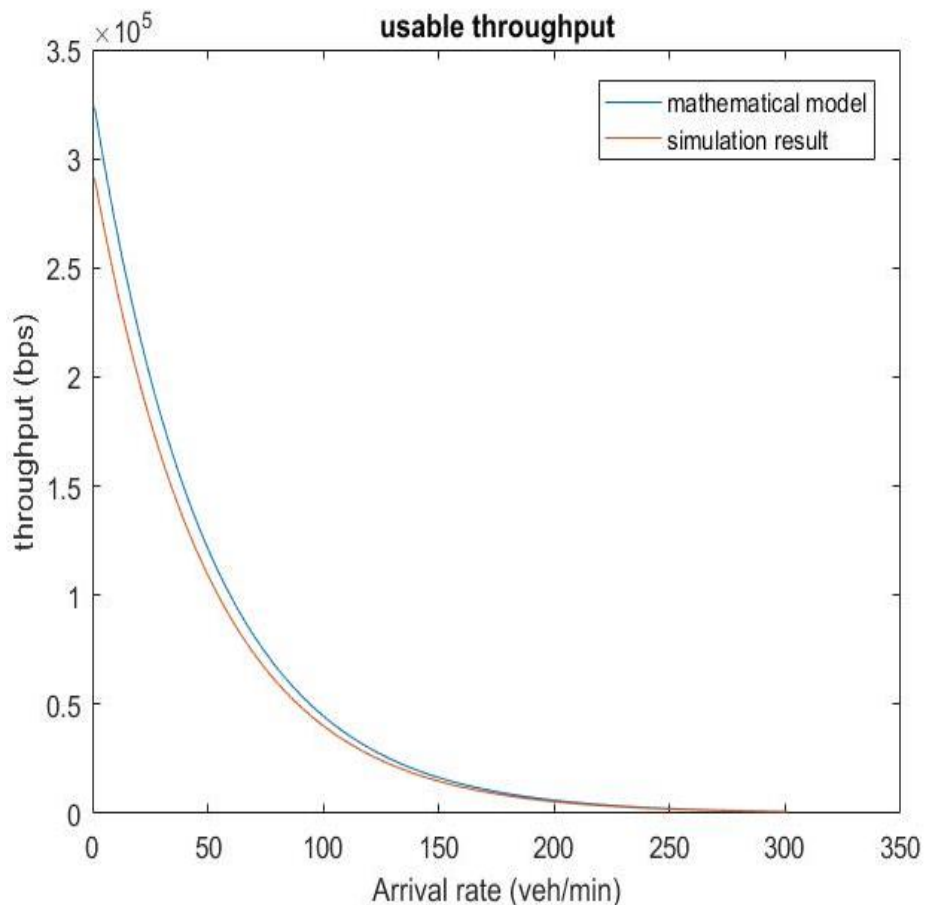


Figure 6.3: Usable throughput

We can see that the usable throughput decreases exponentially as the rate of arrival of interfering vehicles increases for both cases (simulation, mathematical model) until it reaches 150 veh/min. In fact, as the arrival rate of disruptive vehicles increases, the level of congestion will increase, more interference is generated and the usable throughput of visible light communication is reduced.



Figure 6.4 depicts the probability of failure in terms of the arrival rate of disruptive vehicles  $\lambda_2$  (veh/min).

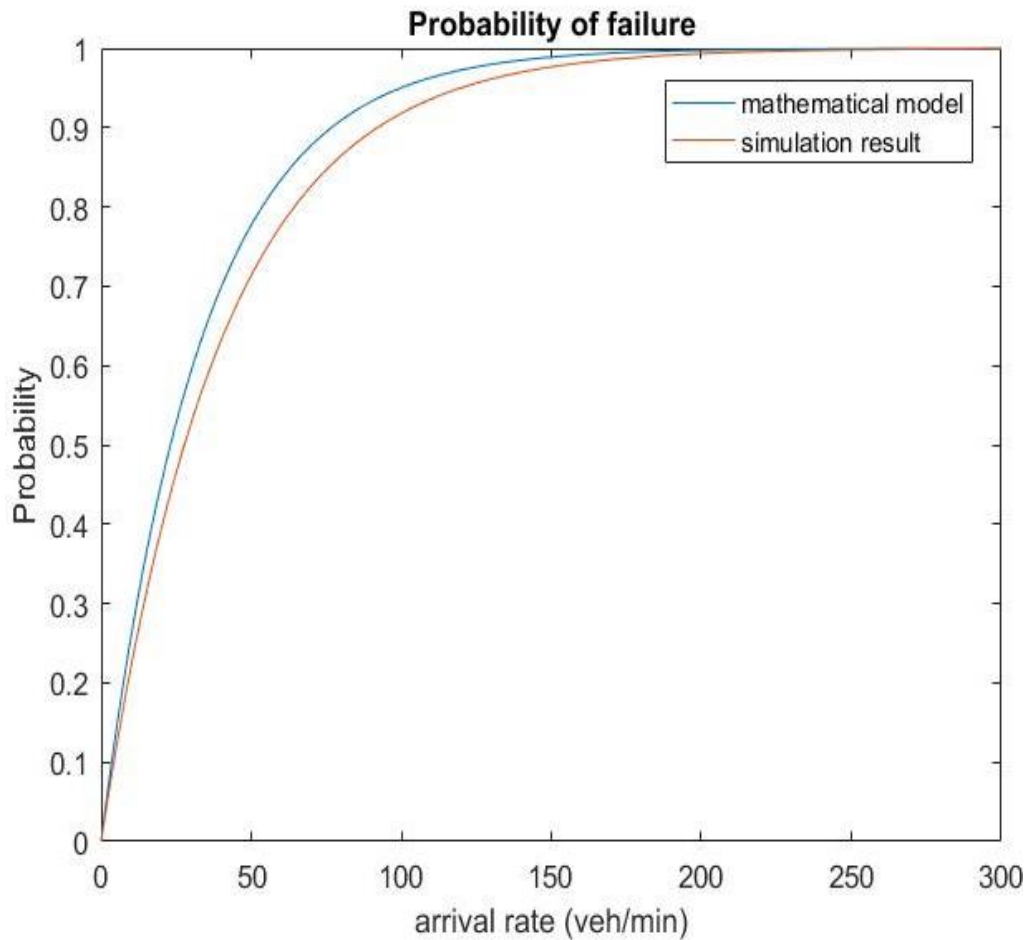


Figure 6.4: Probability of failure

The probability of failure rises with the increase of the disruptive vehicles' rate until it reaches 150 veh/min in both cases (simulation and mathematical model). The arrival rate of 150 veh/min is considered the limiting value, where exceeding this value may affect the VLC. The probability increases due to the light interference induced by the increasing number of interfering vehicles.

Figure 6.5 illustrates the activity period in the function of a number of consecutive disturbances for two different vehicles rates (500 veh/min and 1000 veh/min).

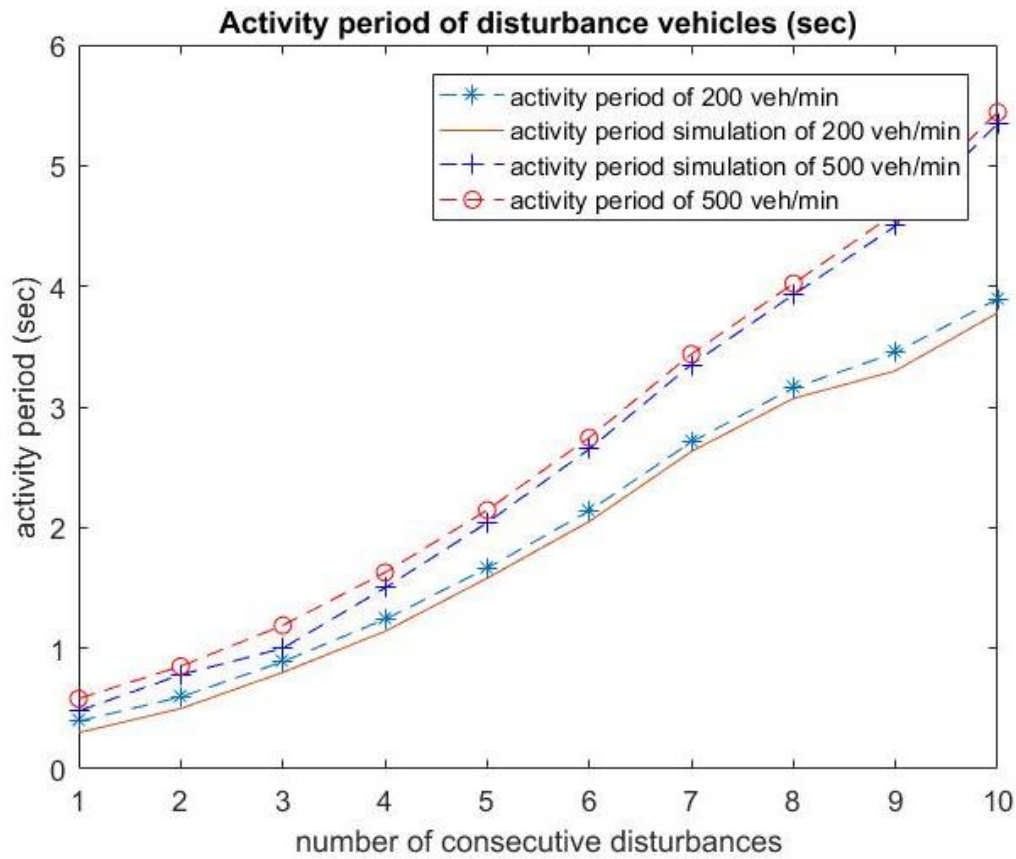


Figure 6.5: Activity period for 200 and 500 veh/min

As we can see, the activity period rises exponentially for 200 and 500 veh/min in both cases (mathematical and simulation model) with the increase of disruptive vehicles. As  $\lambda_2$  increases, vehicular safety distance decreases; this will impact disruption duration.

Figure 6.6 shows the virtual service time (VST1) for two different rates (500 veh/min, 1000 veh/min) in the function of the number of consecutive disturbances.

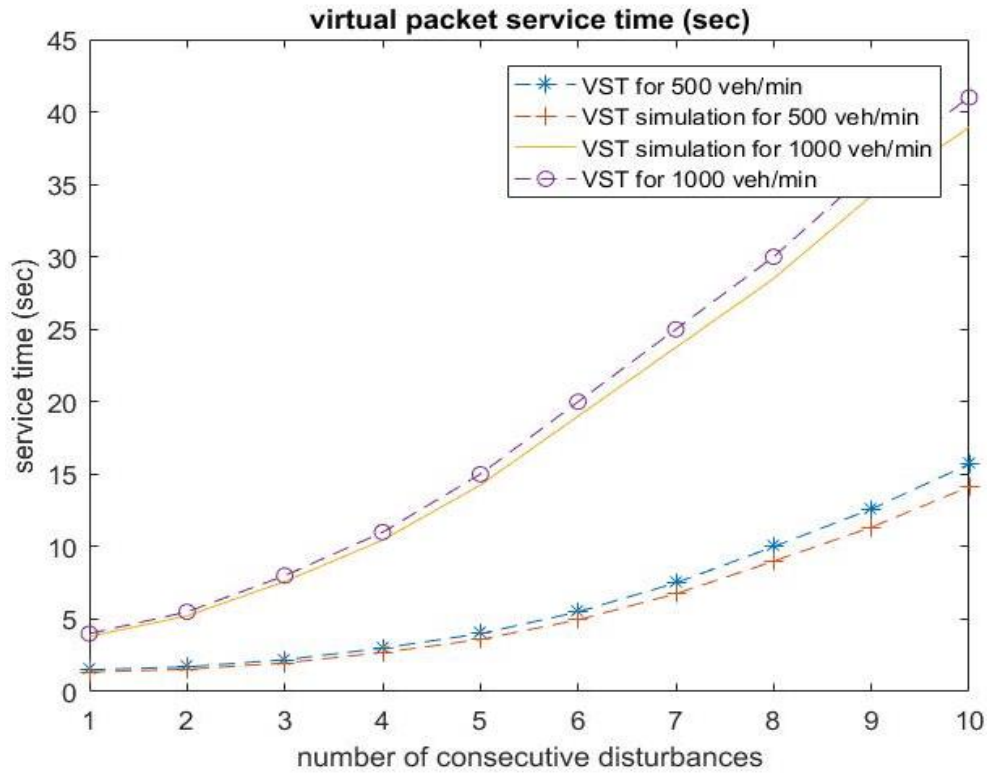


Figure 6.6: Virtual service time (packet)

When  $\lambda_2$  increases, the level of interference increases; this impacts the activity period of platoon vehicles. On the other hand, an increasing number of consecutive disturbances negatively affects the service time of vehicles.

It is noteworthy that figures 3 to 6 show that the mathematical results are highly validated by simulation results.

Figure 6.7 illustrates the probability of K consecutive disturbances followed by a successful packet transmission with respect to the arrival rate of disruptive vehicles.

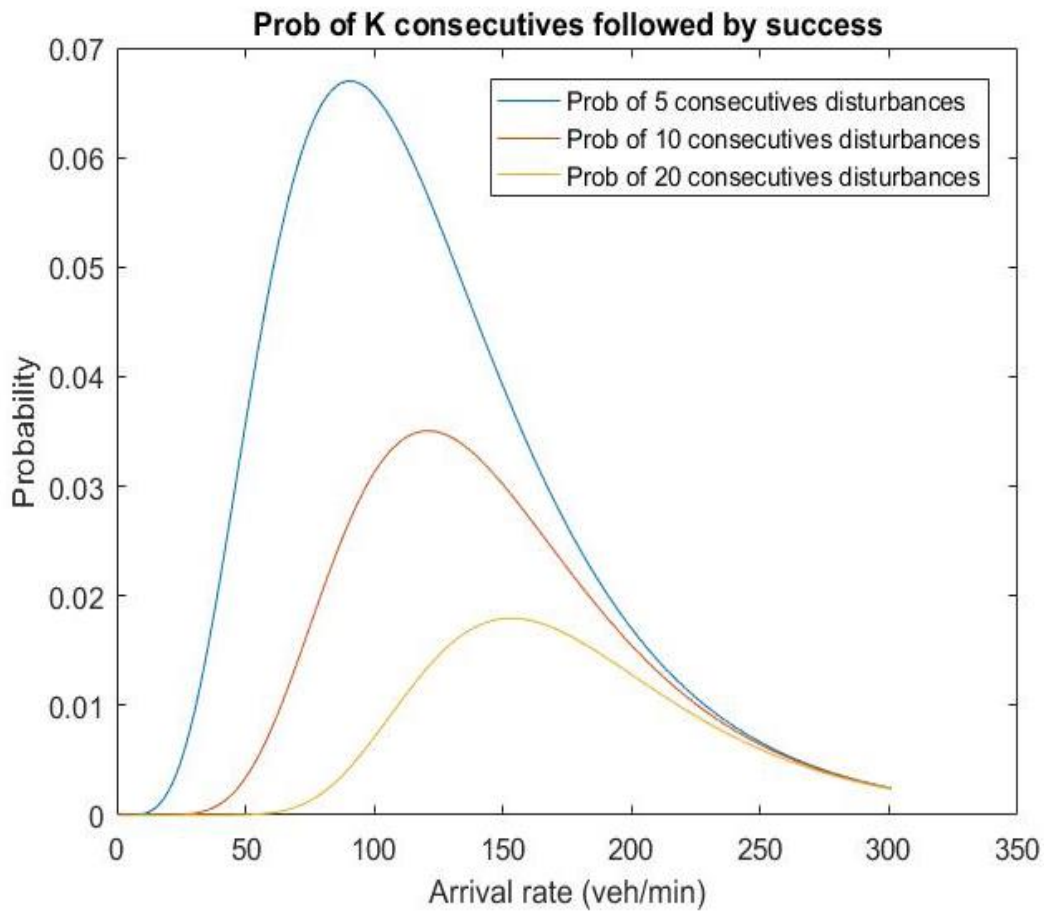


Figure 6.7: Probability of K consecutive disturbances followed by success

We consider a pessimistic scenario with 5, 10, 20 consecutive disruptive vehicles followed by a successful packet transmission. In these cases, the higher the consecutive disturbance, the lower the probability of success. Moreover, the probability follows Gauss law, increases with the arrival rate, reaches a peak (for 100, 120, 130 veh/min resp for 5, 10, 20 disruptive vehicles, and decreases gradually after the peak arrival rate.

## 6.3 Study case 2

### 6.3.1 Real case scenarios

Vehicular networks offer a large portfolio of applications, spanning from safety to traffic management to comfort [153].

In our second case study, taking the same scenario in figure 6.1 but with real cases, we have a special concern to cooperative awareness application executed in a platoon. In fact, the platoon leader should frequently notify platoon vehicles about relevant information, specifically:

- The time needed to arrive at the destination
- The next exit
- The next vehicle to leave the platoon

Therefore, we propose the Platoon Driving Assistance (PDA) application, based on the Cooperative Awareness Messaging (CAM) standard. We modelled the PDA application as exhibited in Figure 6.8. PDA packets are transmitted periodically and carry information gathered from the platoon leader. Each second, the leader sends a message of 400 bytes size with a frequency of 10Hz. The service model parameters are indicated in the following table 6.2.

Table 6.2: PDA parameters

Parameters	Distribution
Packet size	400 Bytes
Packet inter-arrival time	0.1s
Arrival process	Poisson arrival rate

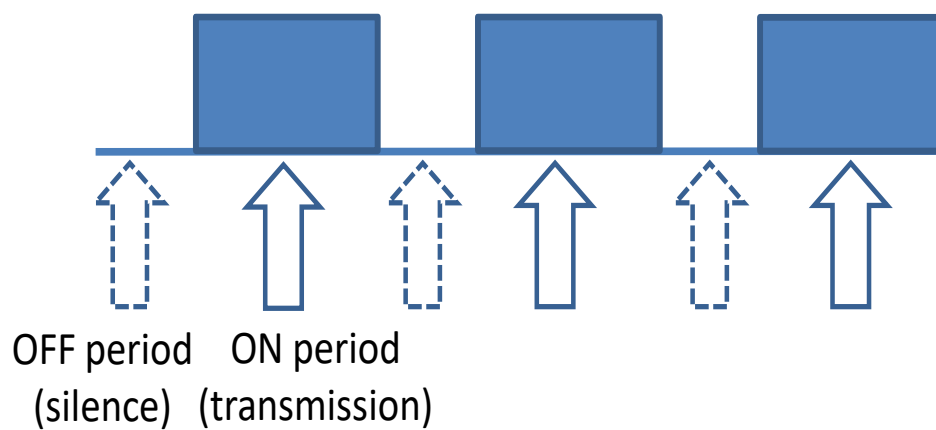


Figure 6.8: Platoon driver assistance application (PDA) modelling

The transmission of PDA packets, exchanged by platoon members, is affected by the disturbing vehicular traffic (vehicular lights). Therefore, we oriented our efforts towards evaluating the impact of the arrival rate of disruptive vehicles on platoon data transmission. We identified four cases that capture four levels of vehicular densities, spanning from high traffic density to sparse traffic density, as depicted in Table 6.3.

**Table 6.3: Case of Disruptive vehicular Traffic Model**

<b>Case</b>	<b>Arrival rate</b>	<b>Service time</b>	<b>Mean velocity V (km/h)</b>
<b>Case 1</b>	Erlang	Erlang	15
<b>Case 2</b>	Exponential	Exponential	35
<b>Case 3</b>	Erlang	Erlang	70
<b>Case 4</b>	Constant	Constant	100

Case one refers to the case of highway entrance or exit where vehicles deaccelerate and present an Erlang arrival model with a low mean velocity (e.g 15 km/h) inducing high vehicular density.

The second case occurs when the traffic density is medium and vehicles start to accelerate with an exponential arrival model and a mean velocity of 35 km/h. Case three arises when vehicles get away from the dense traffic and reach a mean velocity of 70 km/h. Case four refers to sparse vehicular traffic where vehicles experience a constant velocity.

## 6.3.2 VLC Performance evaluation

### 6.3.2.1 Mathematical model M/GI/1

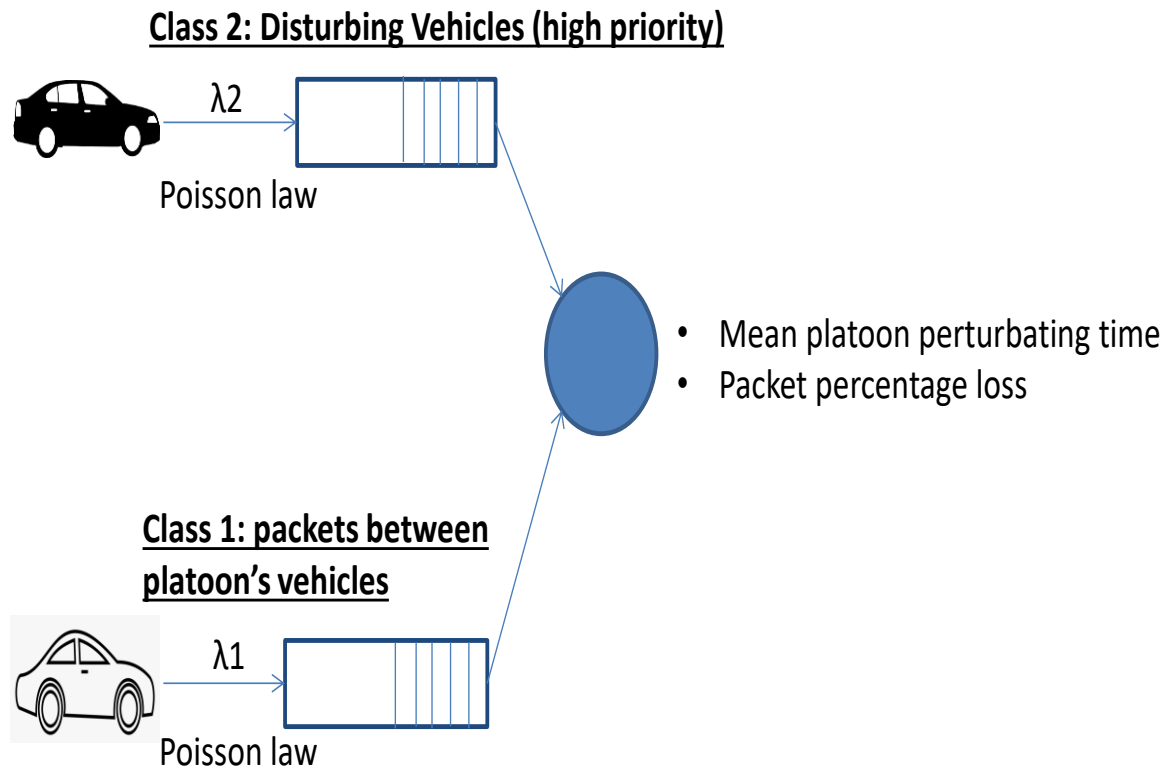


Figure 6.9: Multiclass queuing model

We model the VLC platoon system with an M/GI/1 multiclass queuing model (with two classes of service) which adopts a non-preemptive priority policy for each class of service:

- Class 1 represents packets generated by vehicles platoon (lower priority): Arrival rate of packets follows Poisson with a mean rate  $\lambda_1$  and a load  $\phi_1$
- Class 2 represents disruptive vehicles (higher priority): Arrival rate of disruptive vehicles follows Poisson with mean rate  $\lambda_2$  and a load  $\phi_2$

#### 6.3.2.2 Simulation parameters

The service follows a general law with independent arrivals GI (figure 6.9). We denote by  $E[X_1]$   $E[X_2]$  the mean disruptive time,  $E[W_1]$  the mean packet waiting time and  $E[W_0]$  the mean delay of the packet in service at the moment of the disruptive vehicle arrival.

It is noteworthy that class 2 perturbation time, induced by disruptive a vehicle that is equal to the class 1 mean packets waiting time (class 1). Using Pollaczek-Khinchin (P-K) Formula, we derived the main performance parameters to evaluate the M/GI/1 non-preemptive priority system.

$$E [W_1] = \frac{E [W_0]}{(1-r_1)(1-r_2)} \quad (1)$$

$$\text{where } r_i = \sum_{j=1}^i \varphi_j \text{ and } \varphi_i = \lambda_i \times E[X_i]$$

$$\text{where } E[W_0] = \sum_{i=1}^2 \lambda_i \times E[X_i^2] \quad (2)$$

$$\text{with } E[X_i^2] = V(x) + E[X_i]^2 \quad (3)$$

$$\text{Variance } V(x) = E[X_i^2] - E[X_i]^2$$

CV is the coefficient of variation. It is computed as follows

$$v(x) = CV^2 \times E[X_i]^2 \quad (4)$$

Thus replacing (4) in (3), we obtain

$$E[X_i^2] = CV^2 \times E[X_i]^2 + E[X_i]^2$$

$$E[X_i^2] = E[X_i]^2 [CV^2 + 1] \quad (5)$$

Replacing (5) in (2)

$$E[W_0] = \sum_{i=1}^2 \lambda_i \times E[X_i]^2 [CV^2 + 1] \quad (6)$$

Finally, the mean platoon perturbation time:

$$E [W_1] = \frac{\sum_{i=1}^2 \lambda_i \times E[X_i]^2 [CV^2 + 1]}{(1-r_1)(1-r_2)} \quad (7)$$

$$E [W_1] = \frac{\sum_{i=1}^2 \lambda_i \times E[X_i]^2 [CV^2 + 1]}{(1 - \varphi_1 - \varphi_2)(1 - \varphi_2)} \quad (8)$$

### 6.3.3 VLC Performance results

To validate our mathematical model, we conducted a series of simulations batches performed using SUMO and OMNET. The simulation parameters are indicated in the following table.



Table 6.4: Simulation Parameters

Simulation Parameters	Values
Packet arrival rate ( $\lambda_1$ )	1000 packets/min
Disruptive vehicle arrival rate ( $\lambda_2$ )	0-12 veh/min
Distance between platoon's vehicles (d)	10 meters
Channel speed ( $\mu_1$ )	300 kbps
Number of platoons	60 platoons
Number of vehicles / platoon	2 vehicles/ platoon

Figure 6.10 illustrates the mean platoon perturbation time for the four different cases, in the function of disruptive vehicles arrival rate  $\lambda_2$  (veh/min). Moreover, figure 6.10 depicts results obtained with simulation and mathematical modelling.

The mean platoon perturbation time is not affected by the exponential arrival rate but rather by service time (the speed of the disruptive vehicles).

Figure 6.10 shows that mathematical modelling results are validated by simulation. This proves the accuracy of the multi-class M/GI/1 mathematical modelling.

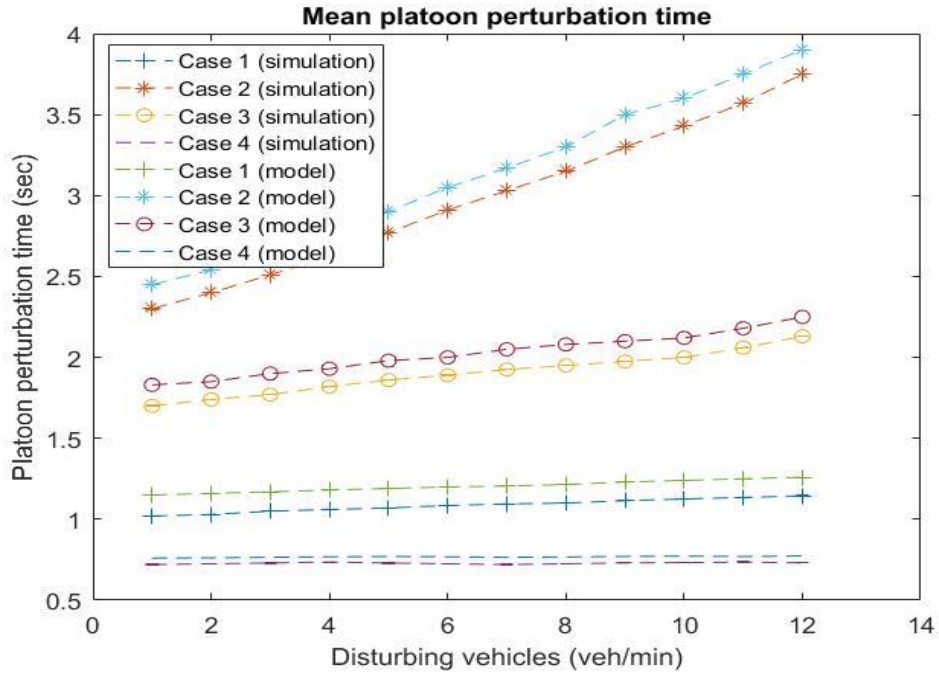


Figure 6.10: Mean Platoon Perturbating Time

The mean platoon perturbation time depends on the velocity of the disruptive vehicles and the vehicular traffic density. With case 1, the disruptive vehicular traffic is dense, inducing a constant mean vehicular velocity. Consequently, the mean perturbation time to the platoon is constant and almost equal to 1sec.

With case 2, the average density and the velocity of disruptive vehicles are higher than in case 1. The average disturbance time of the platoon rises exponentially as the number of disruptive vehicles increases to reach 3.75 sec.

With case 3, the vehicular density is reduced and vehicles accelerate and reach a constant speed. In this case, the average perturbation platoon time rises to around 1.8 sec. With the last case, vehicles present a constant velocity and the average disturbance time remains constant as there is no congestion.

Figure 6.11 illustrates the percentage of packet loss obtained in the 4 different cases.

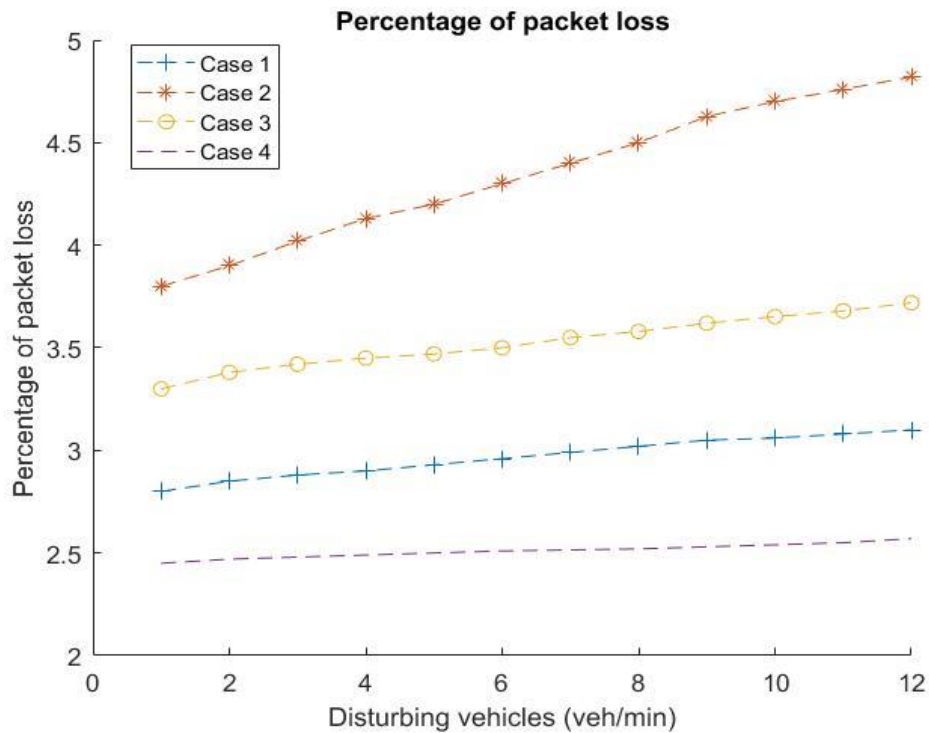


Figure 6.11: Percentage of Packet loss

As we can see, the percentage of packet loss varies from a case to another and is impacted by the vehicular density. Case 1 incurs the lowest percentage packet loss since it presents the highest relative velocity (velocity difference between platoon's velocity and the disruptive vehicles). The highest packet percentage loss is obtained in the second case since it presents the lowest relative velocity.

## 6.4 Conclusion

In vehicular networks, VLC is considered a key reliable technology that transmits urgent messages in a vehicular platoon.

In this chapter, we have tackled 2 different scenarios to study the performance evaluation of VLC for a platoon in the presence of interfering vehicles. We conducted mathematical modelling validated by the simulation to compute the different performance parameters for each scenario. We can conclude that the QoS parameters are highly affected by vehicular traffic. The degradation of VLC quality of service occurs when the vehicular traffic reaches a threshold that is relative to each case.

Therefore, we can draw the following conclusion: in the case of VLC performance degradation, vehicle platoon should switch to an RF technology which will be studied in the next chapter.

# 7. Chapter 7: Vertical handover between VLC and RF technology

## 7.1 Introduction

Despite the benefits mentioned previously and the approved concept of VLC as a communication solution for high traffic density scenarios, the range of technologies is relatively limited, resulting in a short coverage area, where barriers can easily interfere with VLC links and remove the safety requirements of applications.

Furthermore, as discussed in Chapter 2, the RF communication technology standard (IEEE 802.11p) for ITS applications is expected to achieve several metres of coverage. Consequently, the appropriate combination of the two technologies (VLC and RF) for an ITS application is crucial to satisfy security demands.

This chapter deals with the suggestion that allows the handover between VLC and RF communications to improve platoon safety. In order to handle the VLC failures, the exchange of system data should be continuous, using alternative technologies, which guarantee the global quality of service of the system as well as maximising the safety of autonomous driving while keeping low latency.

In this chapter, the vertical HO decision is made on the basis of two different techniques: threshold values and machine learning algorithms for two different scenarios (night and sun cases). The 802.11p and LTE-V are the RF technologies selected after handover. This selection is done based on different criteria and by using two different methods: the utility function and the cooperative game. Finally, this chapter concludes with an evaluation of the selected network.

## 7.2 Vertical handover decision

The VLC platoon performance study shows that QoS parameters are highly affected by vehicular traffic. This degradation in the VLC quality of service occurs when the vehicular traffic reaches a threshold that is relative to each of the four cases (high density, medium density, low density and sparse traffic).

In our research work, we propose a vertical handover network selection architecture that is composed of two main modules: Module 1- VLC Performance Monitoring Module and Module 2- Vertical Handover Decision Module.

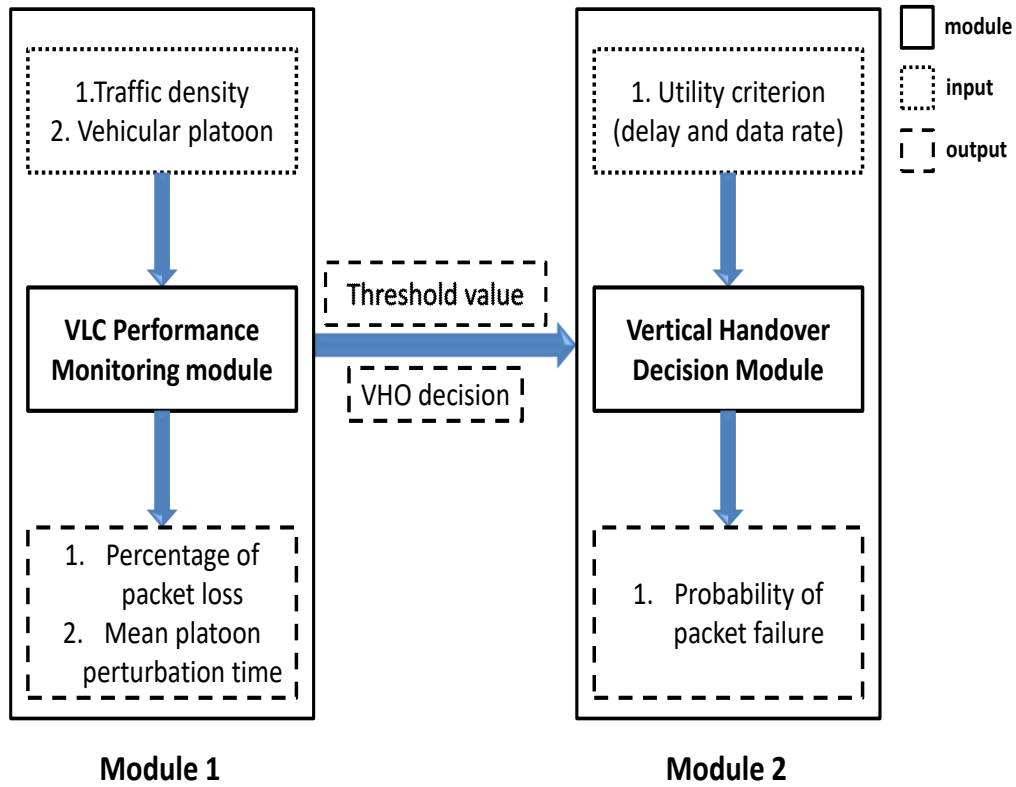


Figure 7.1: Vertical Handover Network Selection Architecture

Module 1 continuously monitors VLC performance parameters in terms of packet loss and platoon perturbation time that is discussed in details in the previous chapter. Whenever these parameters exceed some thresholds value or have VHO decision, module 2 is triggered. The threshold value, VHO decision and the second module are described in the following sections.

### 7.2.1 Threshold value

The threshold value is calculated based on the average percentage loss of packets in each case, calculated in chapter 6, which differ from one case to another.

$$\text{Threshold value} = \frac{\sum_1^N \% \text{ of packet loss}}{N} \quad (1)$$

Where N is the number of disruptive vehicles. We have assumed that the threshold value is static as we can see in table 7.1.

Table 7.1: Threshold value of each case

Case	Threshold values
Case 1	3%
Case 2	4.5%
Case 3	3.5%
Case 4	2.5%

When the QoS degradation threshold value is reached, a vertical handover is triggered to switch critical messages transmission to the RF technology. The present work assumes that the threshold values are static; nevertheless, we envision rendering these values dynamic in future work.

### 7.2.2 Our proposed Platform

In this section, we bring the focus on the VLC performance in the context of a vehicular platoon. More specifically, we investigate the performance threshold that should incur switching to an RF technology. To this end, we devise a platform that aims at taking the vertical handover decision: switching from VLC technology to RF technology. This decision is based on a portfolio of variables that impact the packet loss ratio.

We have developed a platform that provides a vertical handover decision in two different cases based on ML decision. The first case is related to the interference caused by disruptive vehicles at night that is described in details in chapter 6. The second case focuses on sun interference [154].

In the second scenario, we will evaluate the performance of visible light communication in the presence of two sources of interference: disruptive vehicles and sun interference. The sunlight interference is studied between 6:00 and 18:00 as we can see in figure 7.2 (A). It shows the variation of sunlight intensity throughout the day. The disruptive vehicles affect the performance of the VLC during the night, where very low light is detected because the moonlight includes more ultraviolet and less visible waves. From 6:00, the color of the sunlight turns orange and from 8:00 or 9:00 it quickly turns white as we can see in figure 7.3 (B) that shows the color variation. This color is maintained with increasing intensity all day long until noon [155]. From that moment on, we can observe the opposite procedure. The intensity of the sunlight decreases as we advance from noon to evening. From 17:00, we start getting an orange color, and from 18:00, the blue-grey color returns to signal the advent of night.

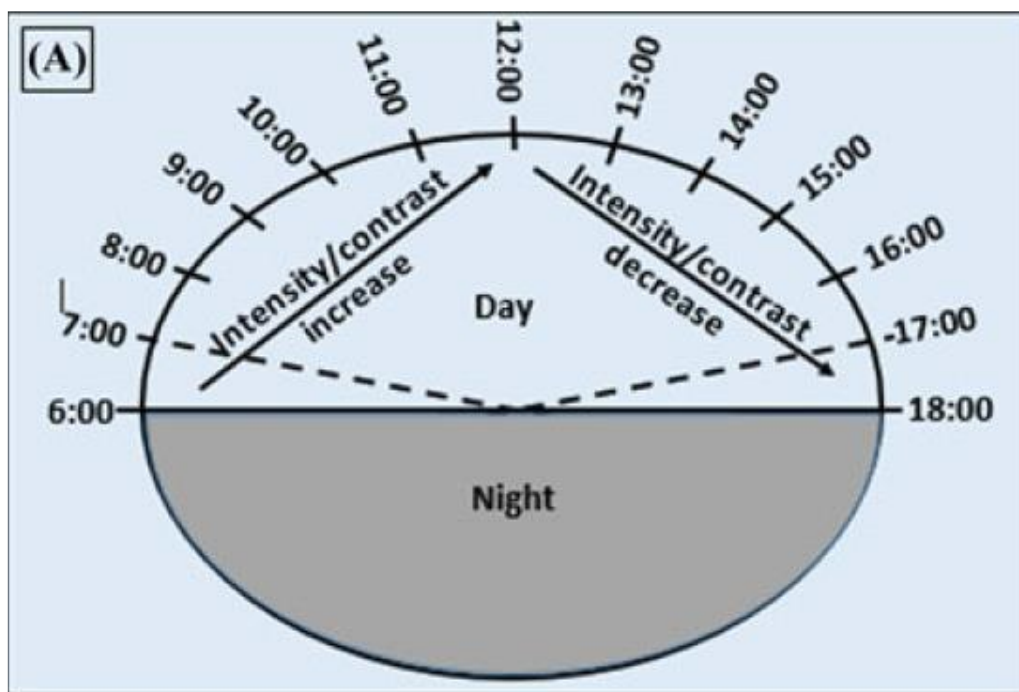


Figure 7.2: The variation of sunlight intensity throughout the day [155]

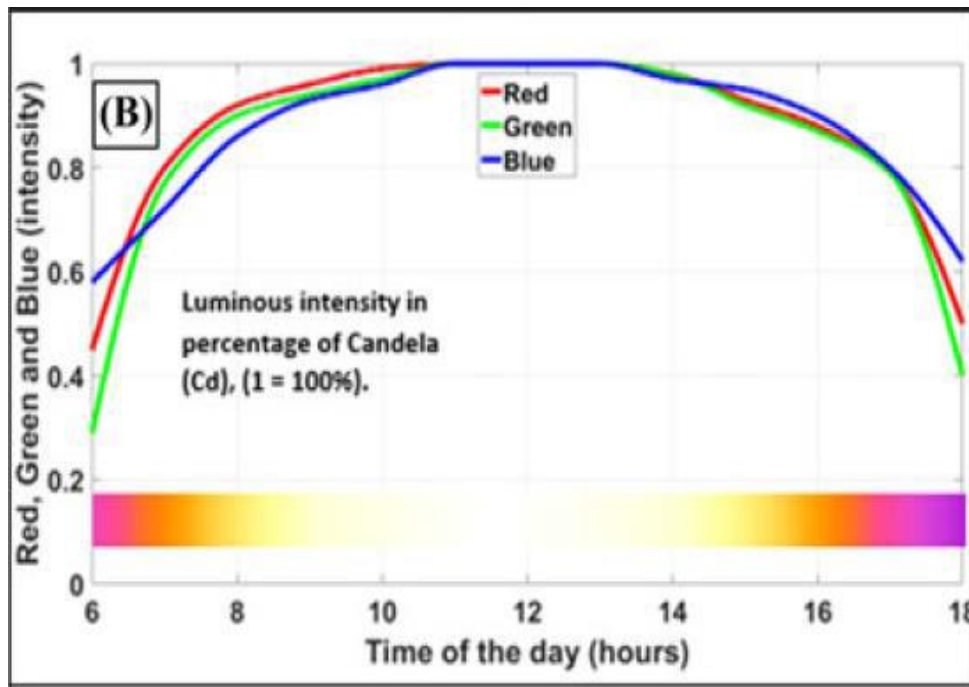


Figure 7.3: Color variation during the day [155]

### 7.2.2.1 Machine learning

Over the past decade, the learning method has grown to become a highly attractive topic for the scientific community. Many studies have covered the topics of machine learning (ML), deep learning (DL) and artificial intelligence (AI). These are considered the core of the learning method (figure 7.4) [154]. AI is a domain based on the automated execution of human tasks, while ML and DL are specific methods to reach this goal. AI does not have any form of learning.

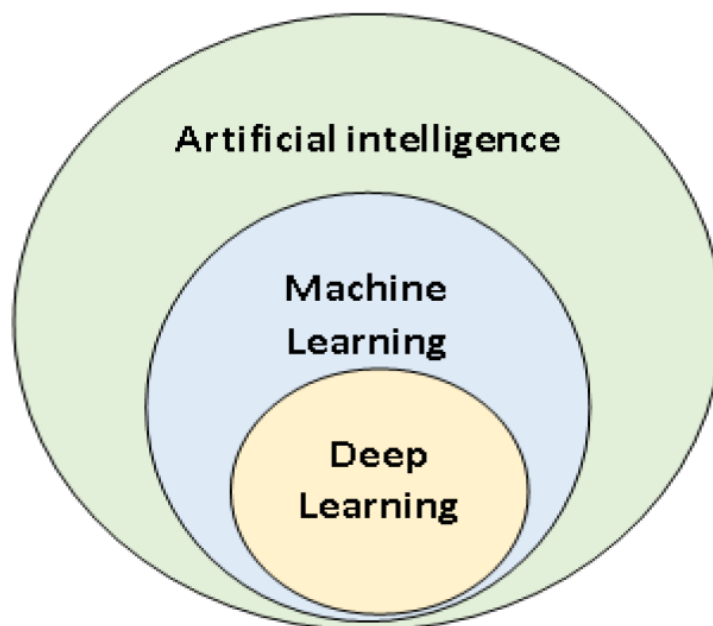


Figure 7.4: Deep Learning, Machine Learning and Artificial Intelligence

Artificial intelligence is considered a sector of computer science that focuses on the analysis and design of intelligent systems that can detect their environment and take measures to optimise the probability of their success. The objective of AI is to provide an intelligent understanding of building computer programs that show an intelligent performance by using inference or reasoning inside the machine. These complicated problems are the ones where ML and DL methods work well.

DL is a part of AI which is based on artificial neural networks. DL algorithms are more adapted to problems with huge datasets; other problems with smaller datasets can be solved simply by using machine learning. It can use supervised or unsupervised algorithms or both. By extracting complex, high-level abstractions as data representations through a hierarchical learning process, DL models produce results more quickly than ML techniques

ML is a domain that focuses on the learning component of AI by building algorithms that represent a set of data as best as possible. Unlike conventional programming in which an algorithm can be coded using known characteristics, ML uses subsets of data to create an algorithm that can use combinations of characteristics that are new or different from those that can be derived from the basic principles. For these reasons, we use the ML where there are four common learning methods, each one useful for solving different tasks: supervised, unsupervised, semi-supervised and reinforcement learning.

#### A. Supervised learning

Supervised learning employs models in the training dataset to match characteristics to the target so that an algorithm can make predictions about future datasets. This approach is considered supervised when the model derives an algorithm from the target characteristic pairs, and it is informed if it has made a correct prediction.

The basic steps of supervised machine learning [112], [156] are:

- Acquire a dataset and split it into separate training, validation, and test datasets
- Use the training and validation datasets to inform a model of the relationship between features and target
- Evaluate the model using the dataset to evaluate the degree to which it can determine the predicted values of the unseen instances

The performance of the algorithm on the training data is compared to the performance on the validation data set. In this way, the algorithm is adjusted by the validation set since the calibration set may differ from the test set.

The main components of supervised ML are:

- Collecting a data set and splitting it into training, validation and data sets
- Using the training and the validation data sets to provide a template of the relationship among the features and the destination

#### B. Unsupervised learning

Compared to supervised learning, unsupervised learning is designed to identify models in a dataset and to classify particular cases in the dataset into these groups. These algorithms are



unsupervised because models that may or may not exist in a dataset are not notified by a test and are allowed to be judged by the algorithm.

Some of the most popular unsupervised learning tasks are clustering, association and exception detection [157]. Clustering, as the name implies, groups instances of a dataset into distinct clusters based on specific combinations of their characteristics.

### C. Semi-supervised learning

Semi-supervised learning can occur between supervised and unsupervised learning, and it is especially helpful for datasets that include both labelled and unlabelled data (i.e., all characteristics appear, but not all characteristics have related targets) [157].

Semi-supervised learning usually occurs when image labelling becomes time-consuming. Semi-supervised learning is often employed for medical images, where a doctor may label a small subset of images and use it to form a model. This template is then used to categorize the remaining untagged images in the dataset. The resulting labelled dataset is then utilized to form a working model that is expected, in theory, to exceed unsupervised models.

### D. Reinforcement learning

Finally, reinforcement learning is a learning method for an algorithm that has a specific challenge where no unique response is accurate, but where an outcome is required. [156], [157] are perhaps the nearest approximation to modelling the human learning experience because it also involves learning by test and error instead of by data alone. Although reinforcement learning is a potentially useful technique, it is not as powerful as the human learning experience itself.

## 7.2.2 Vertical Handover Decision Platform

The platoon vehicles can communicate with each other through their front and rear lights. The various data measurements are collected and stored in a data file located in the platoon leader (section 1), which will be cleaned and processed by section 2. The processed data is then fed into Section 3 which runs the ML algorithm. It will then be determined whether the packet can be transmitted via the VLC or not. If YES (1), the platoon will keep on using VLC. If NO (2), it means that the platoon should switch to RF technology and we will have VHO.

Before starting with the chosen ML algorithms, a framework is designed and consists of three sections as we can see in figure 7.5:

- Section 1: Data file collection
- Section 2: Data processing
- Section 3: Machine learning processing

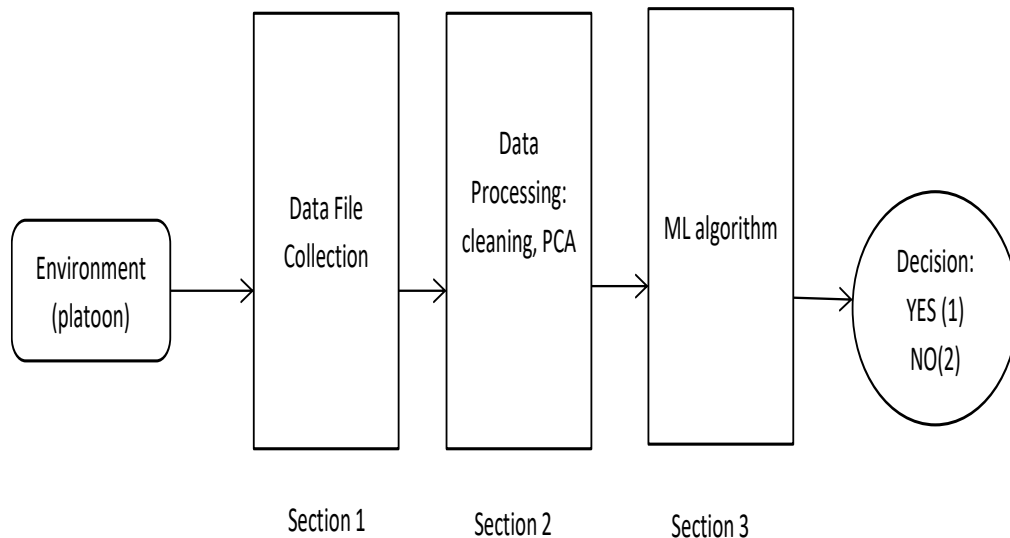


Figure 7.5: VHO decision platoon

### Section 1: Data file collection

Data is collected using a series of simulation batches. We have simulated the study case, detailed previously, using SUMO and OMNET for the two different scenarios. One hundred platoons are tested in our project. At each time-step, data is collected from the “*leader vehicle*” and stored in a data file.

- **Scenario 1:**

Each observation consists of 11 variables:

- Disruptive vehicles arrival rate (vehicle/min)
- Packet arrival rate (packet/min): the rate of packets transmitted in the platoon per minute
- Packet size (bytes)
- The velocity of disruptive vehicles (km/h)
- Relative velocity (km/h): it is the difference between platoon velocity and disruptive velocity
- Distance between platoon vehicles (m)
- Packet transmission time (sec)
- Interference time (sec): mean platoon perturbation time
- Packet service time (sec)
- Percentage of packet loss: it is the probability of failure; i.e. the probability of packets that fail to reach their destination
- Label: Decision

- **Scenario 2:**

During the day, the collected data set presents the following variables:

- Vehicles arrival rate (vehicle/min)
- Data Packet arrival rate (packet/min)
- Data Packet size (bytes)

- Velocity of disruptive vehicles (km/h)
- Relative velocity (km/h)
- Distance between vehicles platoon (m)
- Packet transmission time (sec)
- Interference time (sec): mean platoon perturbation time.
- Time of the day (h)
- Throughput (Mbps)
- Sun irradiance (dBm)
- SNR (dB): signal to noise ratio
- Label: Decision

It is noticeable that scenario 2 presents additional variables: time of the day, SNR and sun irradiance which is the power per unit area received from the sun in the form of electromagnetic radiation that affects the VLC performance in case of sun radiations.

## **Section 2: Data processing and cleaning**

This module is crucial in every project where data analytics is a key component. In our case, it can be divided into two sub-blocks:

- Preprocessing
- Reduce data dimension with PCA analysis

### **Preprocessing**

Within the pre-processing phase, we were concerned with data cleaning. We detected and corrected the corrupted or inaccurate records. We replaced the irrelevant parts of the data by useful data. Within the dataset of scenario 2, “Time of the day (h)” variable had to be encoded by labels between 0 and the number of unique values 1. We used a sklearn module called preprocessing label encoder to achieve that.

### **Reduce data dimension with PCA analysis**

Reducing the number of variables of a data set naturally comes at the expense of accuracy, but the trick in dimensionality-reduction is to trade a little accuracy for simplicity. In fact, smaller data sets are easier to explore, analyze, store, and visualize. It makes analyzing data much easier and faster especially for machine learning algorithms.

Principal Component Analysis, or PCA, is a dimensionality-reduction algorithm that is often used to reduce the dimensionality of large data sets. It transforms the large set of variables into a smaller one where most of the information in the large set is still contained. The application of PCA results in a reduction of the number of input variables from 11 to only 3 for scenario 1, while preserving 90% of the information. Data extracted from scenario 2 does not need PCA or reduction of features. In fact, PCA analysis reveals that 10 of 12 features should be involved in training in order to preserve 90% of the information.

### Section 3: Applying ML algorithms

At this stage, we try to use the ML model accuracy which is the measurement used to determine which model is best at identifying relationships and patterns between variables in a dataset based on the input, or training, data. The latter applies selected ML algorithms that strive to make the optimal decision related to the VHO. The selected ML algorithms fall into the category of supervised ML that are extensively adopted by the research literature for making optimal decisions. Described next are some of the most popular techniques used in ML to solve the classification problems (K-nearest Neighbors (KNN), Support Vector Machine (SVM), decision trees and random forest).

#### A. K-nearest neighbors (KNN)

K-Nearest Neighbors is a non-parametric supervised learning algorithm that solves the classification problems when we do not have any assumptions about the distribution of data in terms of classification probabilities. In other words, the structure of the model is determined from the data set itself. Furthermore, KNN does not require any learning data points for model generation. All training data is used in the test phase, which makes the training faster. However, KNN requires a large memory space to store the training data and needs time.

KNN was implemented in python using a library called sci-kit learn. We used 70% of the training data to train our algorithm, and 30% to test the accuracy. Table 7.2 exhibits the accuracy retrieved with different values of K in our case study. For fixed K, the risk of KNN classifier converges to its limit relatively quickly, at a rate  $T^{-2}$ , as the total sample size, T, increases [158]. For that, we evaluated KNN for multiple values of K, in order to find the best value of K.

- **Scenario 1:**

Table 7.2: KNN accuracy in our scenario

<b>K</b>	<b>1</b>	<b>3</b>	<b>5</b>	<b>7</b>	<b>9</b>	<b>11</b>	<b>13</b>
<b>Accuracy</b>	0.992857	0.995238	0.997619	0.997619	0.992857	0.992857	0.988095
<b>K</b>	<b>15</b>	<b>17</b>	<b>19</b>	<b>21</b>	<b>23</b>	<b>25</b>	<b>27</b>
<b>Accuracy</b>	0.985714	0.985714	0.983333	0.983333	0.985714	0.988095	0.988095
<b>K</b>	<b>29</b>	<b>31</b>	<b>33</b>				
<b>Accuracy</b>	0.990476	0.990476	0.985714				

Table 7.2 exhibits the accuracy retrieved with different values of K. With our collected data, accuracy presents a high value for the small values of K, then it begins to degrade to reach 0.988. at K=27. At K=29 accuracy returns to become 0.9904. In our case, we determine the best K, from our results, which correspond to the highest accuracy (here, K=7).

In fact, KNN may confront three problems [159]:

- KNN's accuracy can be degraded by a simple vote; the vote of K- nearest neighbours according to their distance to the test instance relies on the data distribution
  - KNN's accuracy is typically sensitive to the value of K
  - KNN's accuracy may be dominated by some irrelevant attributes. Relevant attributes are the variables that are relevant for determining the value of output
- **Scenario 2:**

Table 7.3 depicts the accuracy provided by KNN with scenario 2 (sun case). As can see that KNN fails to provide good accuracy: accuracy varies between 83% and 89%.

**Table 7.3:KNN accuracy in case of scenario 2**

<b>K</b>	<b>1</b>	<b>3</b>	<b>5</b>	<b>7</b>	<b>9</b>	<b>11</b>	<b>13</b>
<b>Accuracy</b>	0.866666	0.873333	0.893333	0.88	0.873333	0.88	0.88
<b>K</b>	<b>15</b>	<b>17</b>	<b>19</b>	<b>21</b>	<b>23</b>	<b>25</b>	<b>27</b>
<b>Accuracy</b>	0.88	0.886666	0.88	0.873333	0.86	0.846666	0.853333
<b>K</b>	<b>29</b>	<b>31</b>	<b>33</b>				
<b>Accuracy</b>	0.84	0.84	0.833333				

At this stage, we oriented our efforts towards exploring whether unsatisfying accuracy is due to data distribution and to overfitting. Therefore, we tuned the parameter K with cross validation, where the best K is the one that corresponds to the lowest test error rate [160].

M-folds cross-validation randomly divides the dataset into M folds. The first fold is considered as validation set and KNN is fit on the remaining M-1 folds. This procedure is repeated M times; each time a different group of observations is treated as a validation set. This process results in K estimates of the test error which then is averaged out (Figure 7.6). The accuracy of KNN according to cross validation is shown in Table 7.4.

**Table 7.4: KNN accuracy using cross validation (scenario 2)**

<b>K</b>	<b>1</b>	<b>3</b>	<b>5</b>	<b>7</b>	<b>9</b>	<b>11</b>	<b>13</b>
<b>Accuracy</b>	0.858	0.87799	0.88599	0.88599	0.884	0.876	0.896
<b>K</b>	<b>15</b>	<b>17</b>	<b>19</b>	<b>21</b>	<b>23</b>	<b>25</b>	<b>27</b>
<b>Accuracy</b>	0.892	0.886666	0.888	0.88	0.874	0.866	0.858
<b>K</b>	<b>29</b>	<b>31</b>	<b>33</b>				
<b>Accuracy</b>	0.86	0.858	0.86				

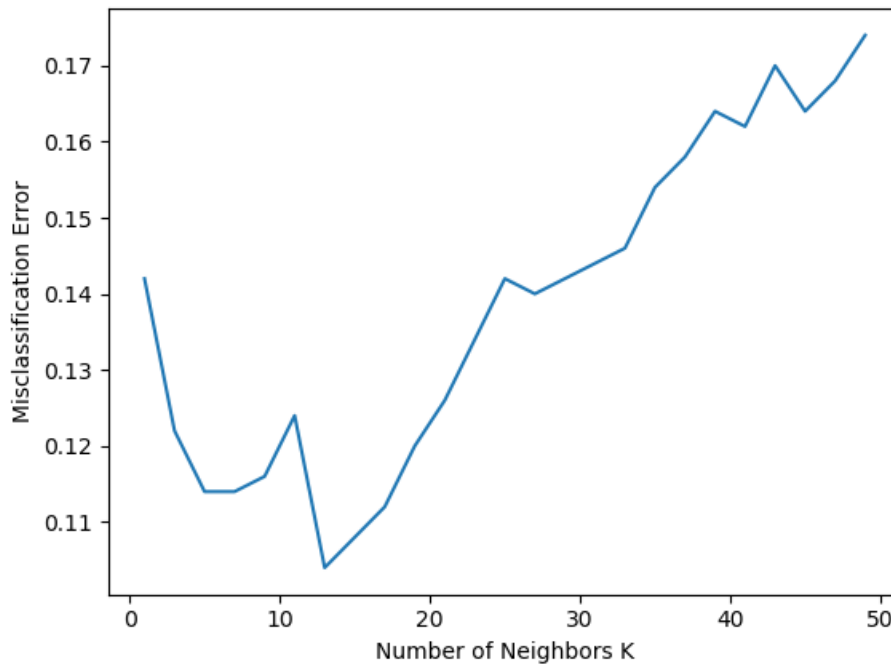


Figure 7.6: Misclassification error of KNN

Results reveal that KNN does not achieve good performance with scenario 2. It is to be noted that the dataset does not present overfitting since accuracy using cross validation is also low (85% - 89%). Moreover, misclassification error is relatively high for all values of K. This result has led us to process the data with other ML algorithms.

### B. Support Vector Machine (SVM)

The second popular technique used in ML is the Support Vector Machine that is considered a supervised learning machine based on statistical learning theory that can be used for model regression and recognition. The theory of statistical learning can accurately describe the components that must be involved to effectively perform some simple types of algorithms.

However, real-world applications typically require more complex models and algorithms (such as neural networks) that make them much more difficult to be analysed theoretically. SVMs can be seen as being at the intersection of learning theory and learning practice. SVM can be considered as a linear algorithm in high-dimensional space.

- **Scenario 1:**

We applied the SVM model to the processed dataset. The SVM model is implemented in python using a library called sci-kit learn. The training data set is divided into two sets with (30%, 70%) proportions. It is to be noted that SVM has two kernels: linear and radial basis function RBF.

Table 7.5: SVM accuracy

Training data	Linear SVM	RBF SVM
1400 samples	0.707142	0.721428

Results indicate that accuracy of SVM model is less than KNN accuracy. To better understand the SVM prediction and the reason for low accuracy, we project our data with SVM kernels on the first two highest varied principal components. Figure 7.7 shows SVM using linear and RBF kernel.

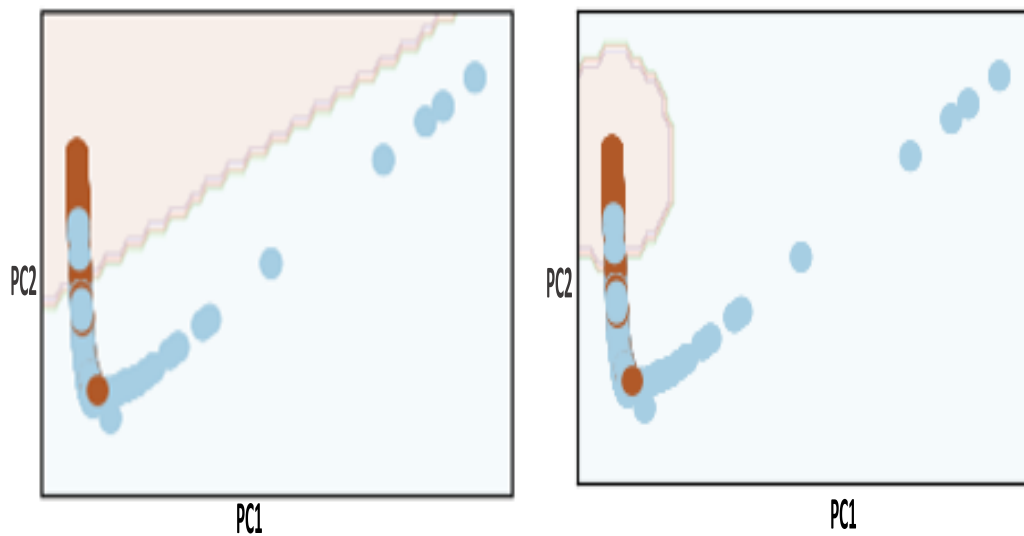


Figure 7.7: Linear and RBF SVM on the two highest PCs for scenario 1

Results indicate that accuracy of the SVM model is less than the accuracy of KNN. To better understand the SVM prediction and the reason for low accuracy, we project our data with SVM kernels on the first two highest varied principal components.

In the two plots, red data represents points of class 1 where the performed decision is “stay with VLC,” and blue data corresponds to points of class 2 where the decision is “switch to RF.” Plots depict how the hyper-plane founded by SVM to perform classification does not differentiate the two classes very well. Hence, the model performs a low accuracy.

- **Scenario 2**

Table 7.6: SVM accuracy (scenario 2)

Training data	Linear SVM	RBF SVM
1400 samples	0.66666	0.64666

The SVM model is trained without applying PCA to the data as pointed out in the previous subsection. Results show that a linear SVM hyperplane can separate the 2 classes with high test accuracy.

### C. Decision Tree

The third technique is the decision trees, which is considered one of the most popular approaches to represent classification schemes. It is a predictive tool that is applicable for both classification and regression tasks. Decision trees are the most performing algorithms that belong to supervised algorithms. Researchers from various fields such as statistics, machine learning, pattern

recognition and data mining have tackled the problem of how to grow a decision tree from the available data that is composed of different types of nodes.

Decision tree modelling was implemented in python using a library called sci-kit. Train-Test-Split technique which is used to evaluate the model's performance.

Here is an understanding of tree and its parameters:

1. Feature name: Feature at every node is decided after selecting a feature from a subset of all features using Gini or information gain
2. Split value: it is decided after selecting a threshold to give the highest information gain
3. Gini or Information gain. It is defined as:
  - Information gain = entropy (parent)-Sum of entropy (child)
  - Gini used to select feature at subsequent node and pick the best split value
4. Samples: number of samples remaining at that particular node
5. Value: number of samples of each class remaining at that particular node. The value = [x,y] refers to x samples using RF technology and Y samples using VLC technology

- **Scenario 1:**

We can see the decision tree of our data (Figure 7.8). When investigating the decision tree, we draw the following analysis:

- The root split node is related to the percentage packet loss, which is crucial in the decision-making process whether VLC is still useful or switching to RF technology is needed.
- In the case of night-time, the relative velocity which is the difference between the speed of the disruptive vehicles and the velocity of the platoon, highly affects the percentage of packet loss. In fact, in the case of night-time, the primordial source of interference is the disruptive vehicle.
- If the percentage of packet loss is less than or equal to 2.503%, and if the relative speed is less than or equal to 27.95 km/h with cases 1 and 2, the visible light communication is not affected by the disruptive vehicles.
- Whenever the relative velocity is greater than 27.95 km/h, either platoon velocity or disruptive velocity is higher than the other. In this case, interference time is small and VLC should be kept.
- In case 1 or 2, platoon vehicles should keep VLC technology unless the percentage of packet loss exceeds 3.492%.
- In case 3 or 4, when the percentage of packet loss is over 2.503%, the platoon will switch to an RF technology because the VLC is not efficient anymore.



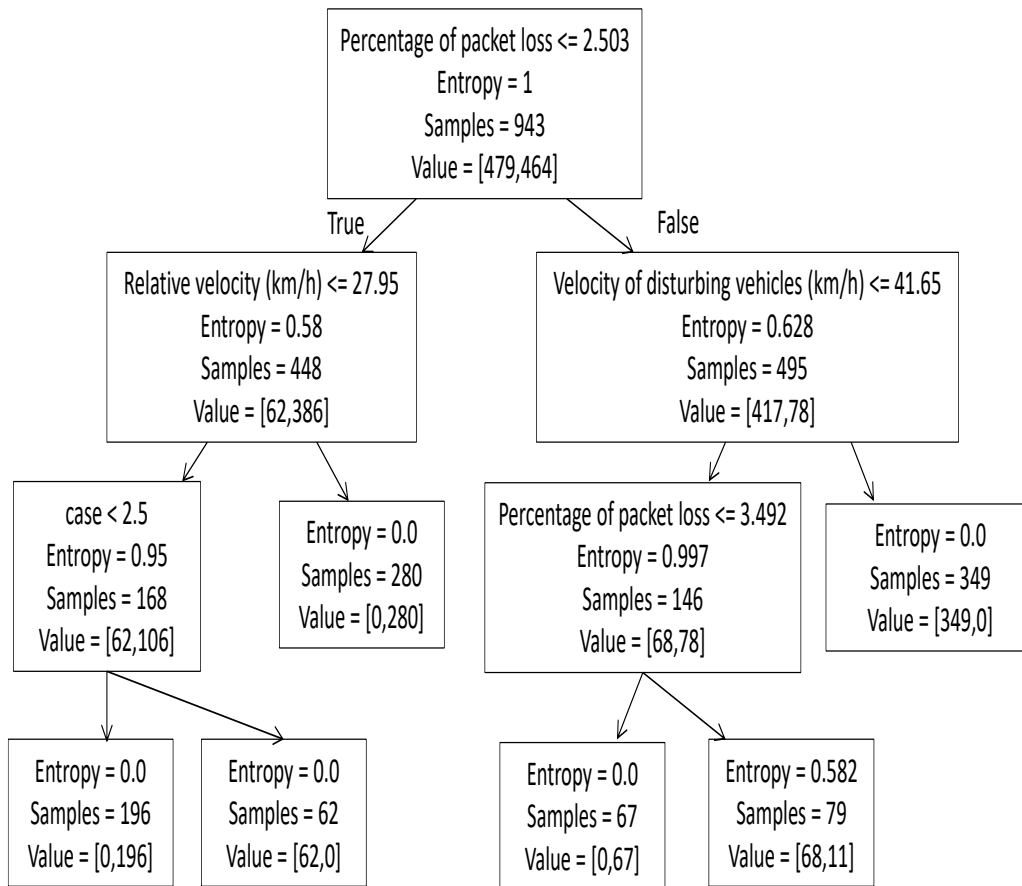


Figure 7.8: Visualisation of the decision tree

To evaluate the decision tree model, we worked on the training and test accuracies (as we see in Table 7.7).

Table 7.7: Decision tree test and accuracy

Data	Training	Test
Accuracy	0.985714	0.985714

- Scenario 2:**

With scenario 2, the decision tree is not expressive theoretically as we can see in figure 7.9. Therefore, It takes only interference time as a split feature. It involves the role of sun irradiance and that of disruptive vehicles in just one feature and gives the decision.

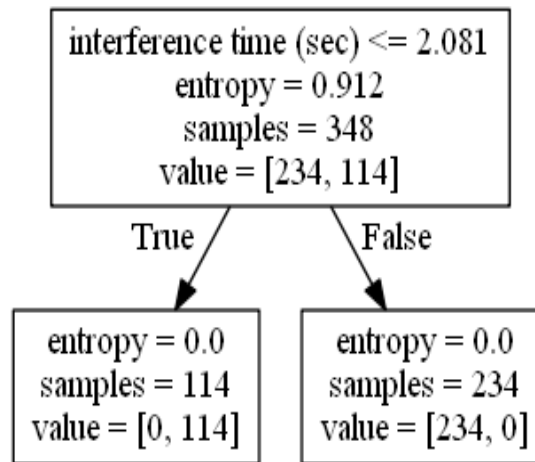


Figure 7.9: Tree plot of scenario 2

Hence, the decision tree is not adequate for our study case. This result makes it necessary to evaluate Random Forest.

#### D. Random forest

The last technique is the random forest that produces multiple decision trees [161]. Trees predict the outcome class, and the majority vote among trees is used as the model's final class prediction. Each branch of the tree represents a possible decision, occurrence or reaction. Random forest is used due to the high accuracy where it runs efficiently in a large database which produces highly accurate predictions. By using the decision tree we have the capability to estimate the missing data and reduce the probability of having overfitting.

Building random forest passes through 2 steps:

- The first step is the creation of a bootstrap dataset that has the same size of the original dataset
- The second step is the creation of a decision tree using the bootstrap dataset by using a random subset of variables or feature at each step.

Random forest modeling is implemented in python using a library called sci-kit learns. The training data set is divided into two sets, with (30%, 70%) proportions. We select three of the classifiers or trees. Among all the features used to train random forest, it will be more informative if we get to know which features are more important in modelling. Sometimes a training model only on these features will perform better results. As shown in Figure 7.10, the percentage of packet loss, case, interference time and packet arrival rate are the most important features.

- **Feature importance:**

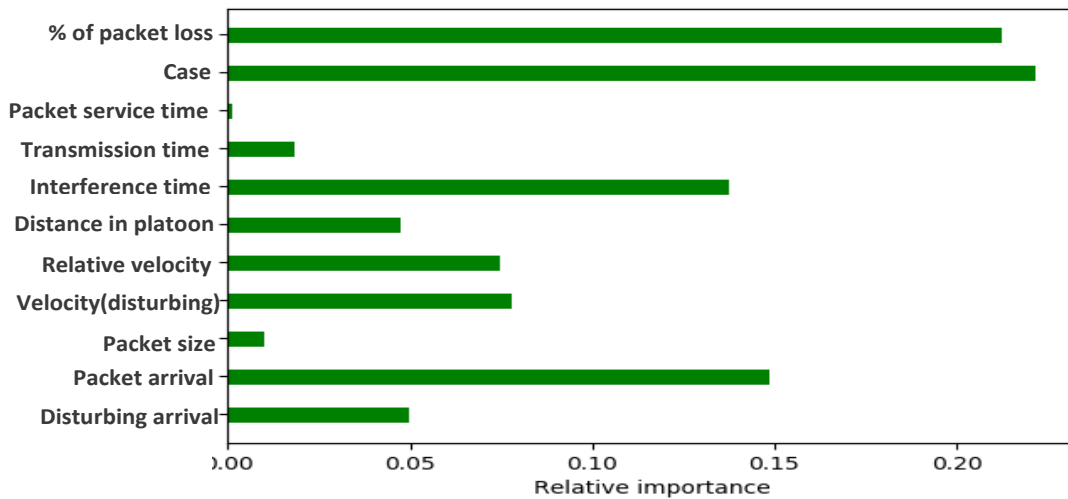


Figure 7.10: Important feature for better classifier

- **Tree plot**

Random forest consists of three classifiers each one of them has six as depth. We have to elaborate on these 3 estimators and their different splitting patterns. We need to also know the extent to which random forest well reflects the scenario of our study.

In Tree 1, seven features are taken into consideration and the number of samples of each class remaining at each particular node is small. Hence, the random forest can cope with a variety of new input variables, samples, and new situations.

When analyzing tree 1, we may conclude the following:

- In general, whenever the packet loss percentage is less than 2.503 with interference time less than 0.776 sec, the platoon can keep the VLC technology.
- In case 1 or 2, when interference time is between 0.776 sec and 1.497 sec and transmitted packets are lost with less than 1.654 %, the platoon should complete transmission via VLC.
- A vehicle within a platoon cannot transmit a packet that needs more than 0.919 sec to be served to the destination via VLC if the percentage of packet loss exceeds 1.654 %, with [0.776-1.497] sec of interference time.
- When the percentage of packet loss exceeds 2.503% and the relative velocity is between 13.2 km/h and 33.05 km/h, a packet that needs more than 1.182 sec to be served to the destination should be transmitted through an RF technology.

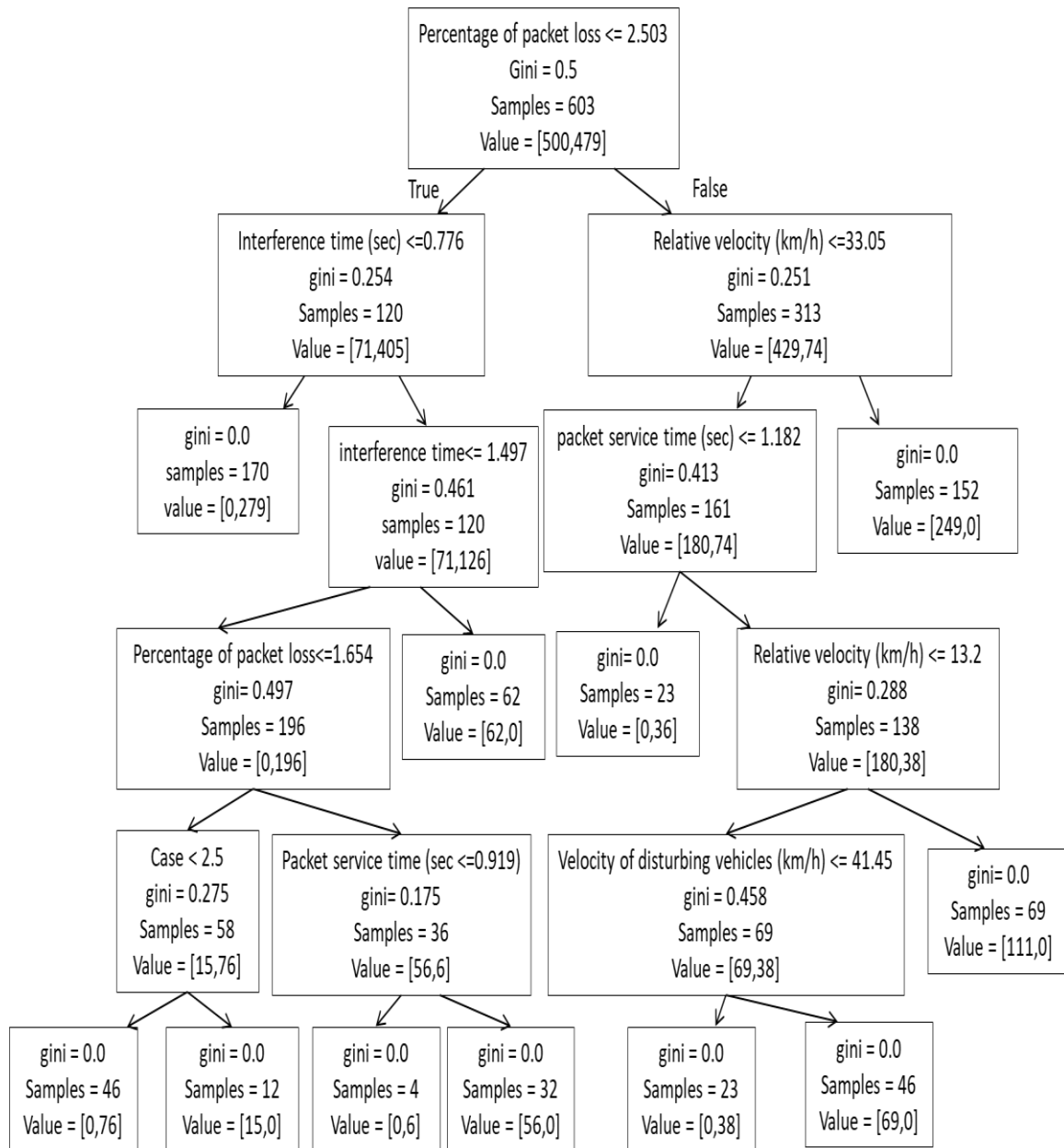


Figure 7.11: Tree 1

By studying tree 2, we may conclude the following:

- When the distance between platoon vehicles is less than 6.255 m and interference time is less than 0.778 seconds, vehicles should communicate with VLC.
- When the interference time exceeds 0.778 sec, the tree split with the percentage of packet loss feature is under 1.113% threshold. This finding is logical since the more the channel perturbation is, the more the packet transmission failure is.
- In the other branch of tree 2, the distance between platoon vehicles and interference time are linked by the “case” feature which reflects the velocity of disruptive vehicles.

Analysing tree 3, gives us the following conclusion:

- Whenever the platoon transmission channel has a packet arrival rate less than 269 packets/min, platoon vehicles communicate via VLC.
- In case 3 or 4, the platoon should switch to an RF technology when the packet arrival rate is more than 269 packets/min.
- In case 1 or 2, when the packet arrival rate is more than 269 packets/min, and the channel has more than 3.535% of packet loss, the platoon should switch to an RF technology.

The evaluation of the random forest gives an accuracy of 0.997619.

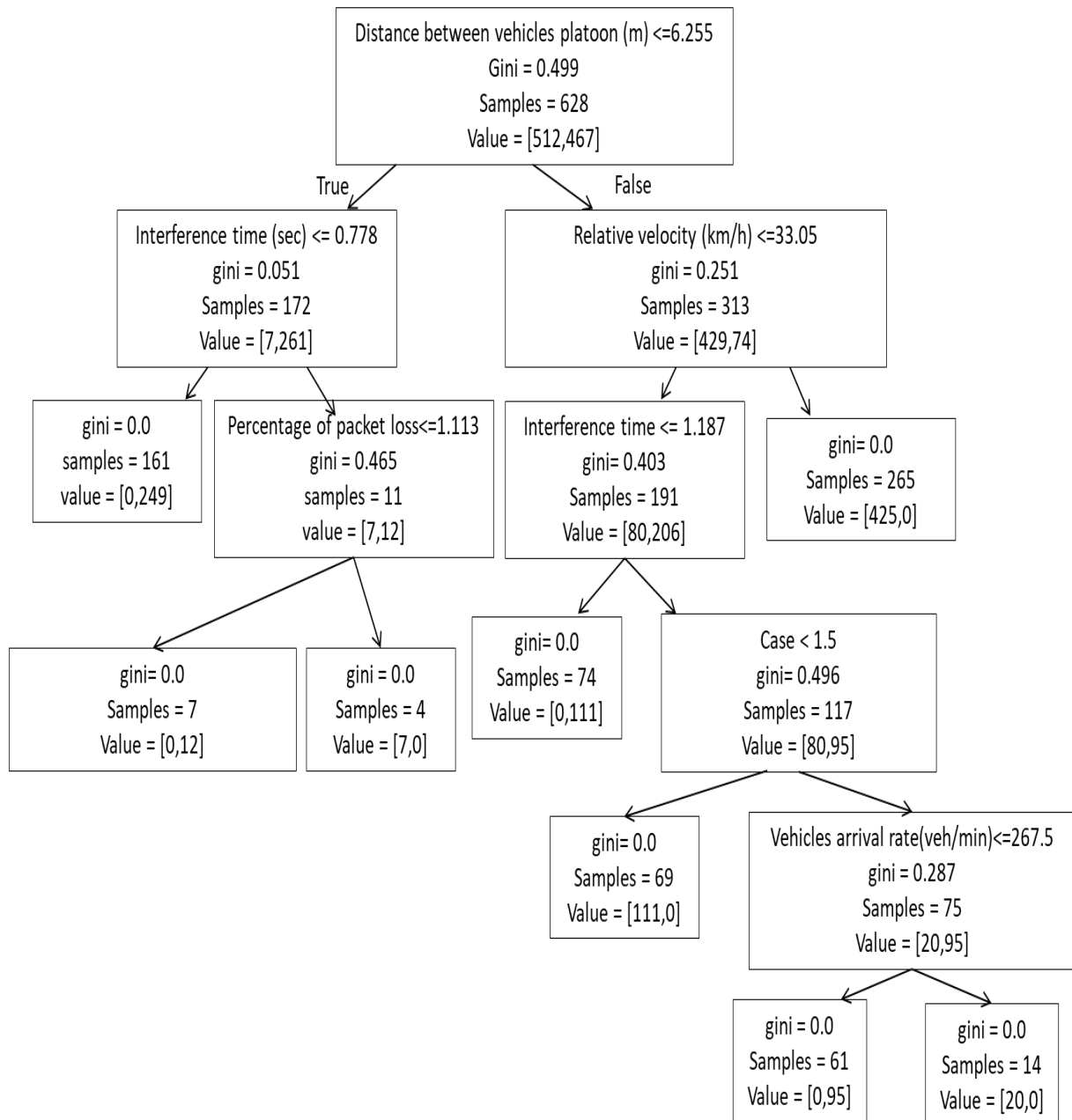


Figure 7.12: Tree 2

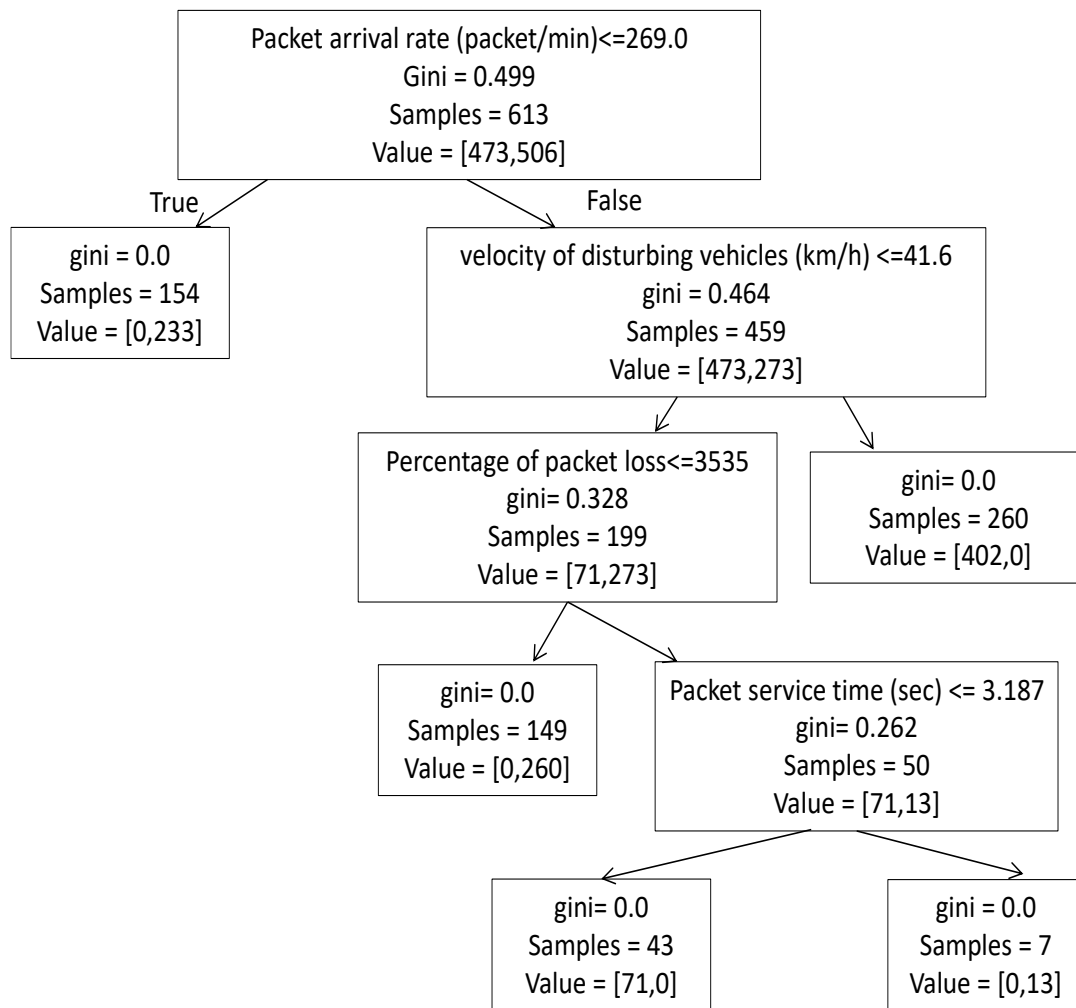


Figure 7.13: Tree 3

- **Scenario 2**

*Feature Importance*

With scenario 2, we proceed similarly to scenario 1. We start by depicting the feature importance then we implement sketching the visualization of random forests trees.

Figure 7.14 plots the feature importance of each dataset parameter. As can see that platoon distance and relative velocity have the most importance.

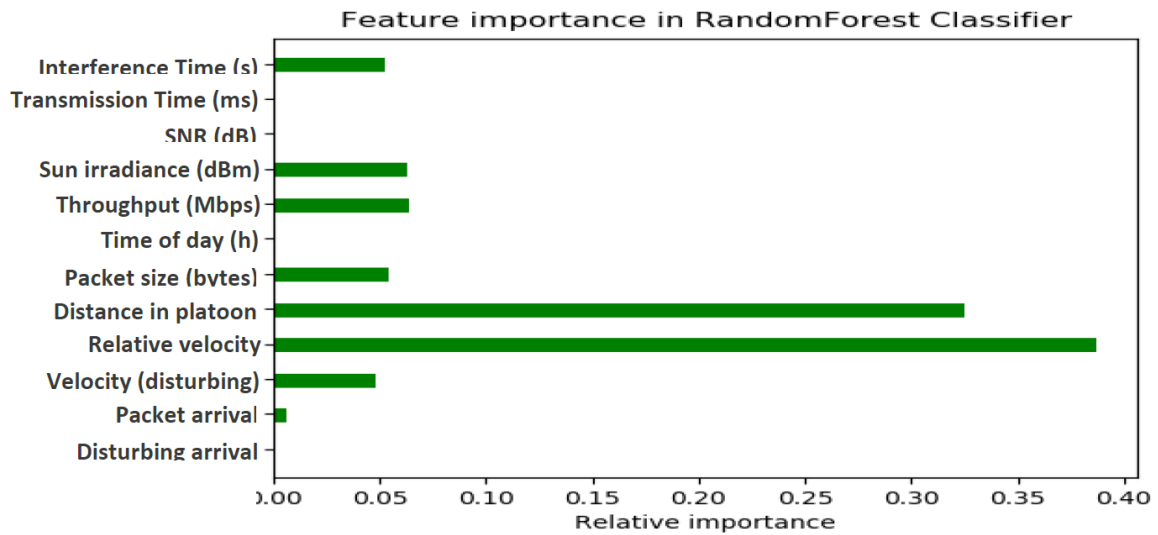


Figure 7.14: Important feature in scenario 2

### Tree Plot

The following figures illustrate the random forest results obtained after 30 times of training. Our 3 estimators have satisfying depth since they are not large. In fact, in a large tree, the well-known fragmentation problem leads to an inaccurate estimation probability.

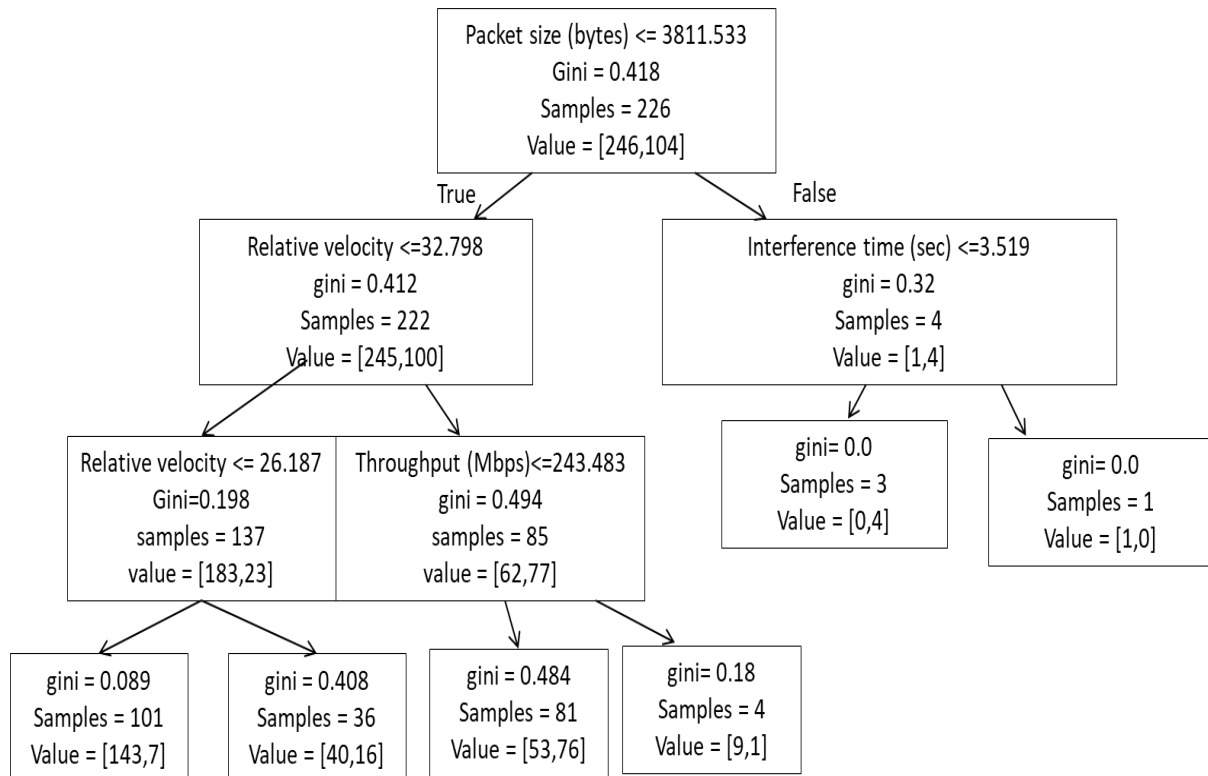


Figure 7.15: Tree 1

For the first tree:

- When the packet size is small and the relative velocity is less than 32.789, the tree will check how much data can be transferred per second (throughput). If the throughput is less than 243.483 Mbps, the platoon cannot transmit via VLC and should switch to an RF technology.
- For the right branch, when the packet size is large, the tree checks the first platoon perturbation time (interference time) which relates both perturbation sources. If it is more than 3.519 sec, switching to an RF technology is preferable to prevent information loss.

For the second tree:

- The tree begins splitting by solar irradiance. When the irradiance time exceeds 16.602, the sun almost breakdowns the visible light communication into a platoon. RF technology is more preferable in this case.
- When sun irradiance < 16.602 dBm and interference time is less than 2.081 sec, the platoon channel that is more than 347 packets/min should switch to an RF technology.

For the last tree:

- When the platoon highly interferes and its channel and transfers are more than 3.787 bytes per second regardless of packet size, the platoon should switch to radio frequency technology.

In general, our random forest is an expressive model. However, this algorithm has a fluctuation of accuracy between 85% and 99%; this is driven by the feature that the model assigns importance to.

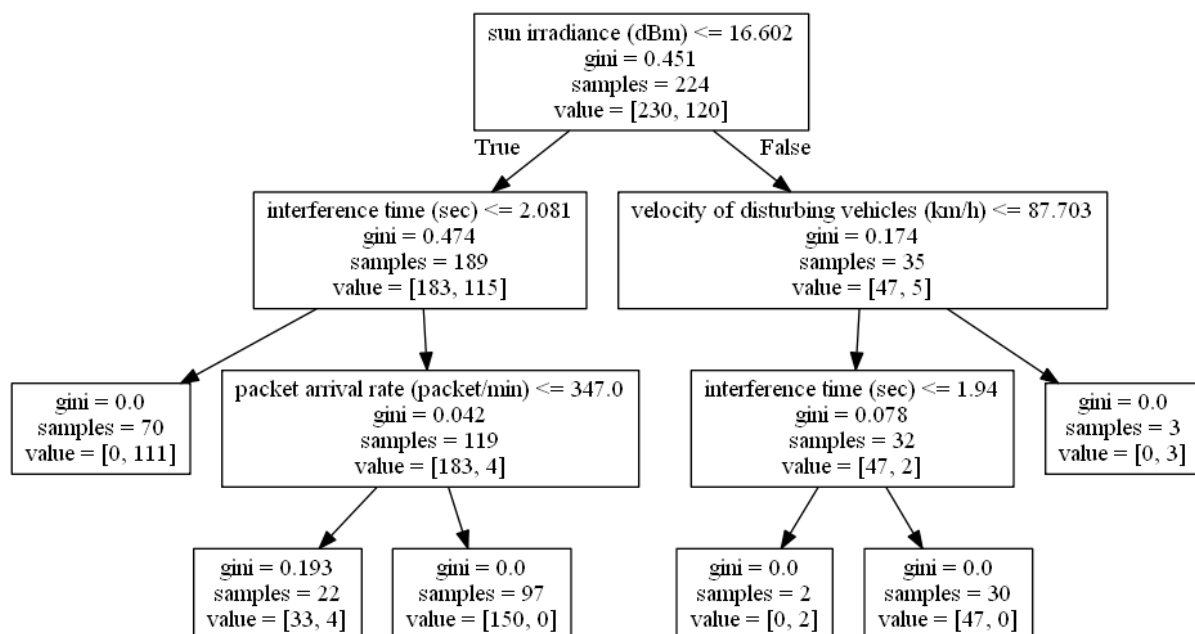


Figure 7.16: Tree 2



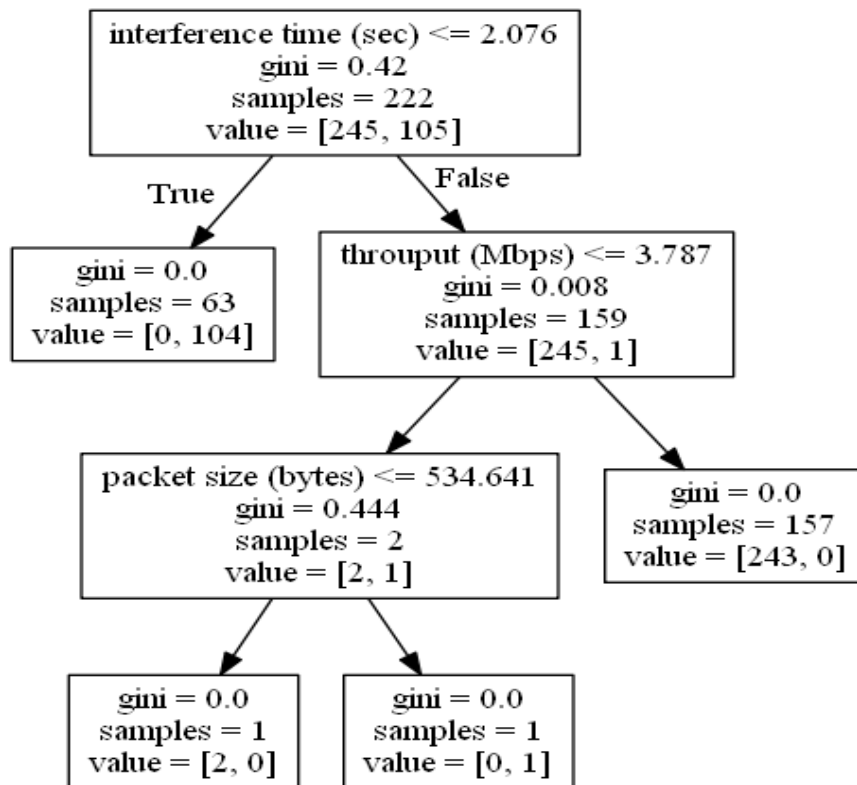


Figure 7.17: Tree 3

### 7.2.3 Decision analysis

As mentioned in the previous section, decision making has been achieved using different machine learning algorithms. Therefore, the performance evaluation of these ML algorithms is very crucial.

Accuracy is definitely an important measure that indicates how the model correctly predicts, but it is not enough to obtain a complete picture [162]. For this reason, we have presented our models through some of the best known classification measures in order to provide a detailed evaluation of their performance.

In this section, first of all, we will define the following classification metrics: Confusion matrix, F1-measure, Log Loss, AUC ROC and MCC. Then, we will compare the different ML algorithms based on these classification metrics.

#### 7.2.3.1 Confusion Matrix

The confusion matrix table consists of four outcomes as we can see in table 7.8, where:

- TP (True Positive): the actual decision and the predicted model remain with VLC
- TN (True Negative): the actual decision and the predicted model switch to RF
- FP (False Positive): the actual decision remains with VLC and the predicted model switches to RF
- FN (False Negative): the actual decision switches to RF and the predicted model remains with VLC

Table 7.8: Confusion matrix

Label	Predicted 1	Predicted 2
Actual 1	TN	FP
Actual 2	FN	TP

### 7.2.3.2 Recall, Precision and F1-Measure

Recall shows the proportion of actual positives correctly classified, where:

$$Recall = \frac{TP}{TP+FN} \quad (1)$$

Recall = 1 means that FN= 0. Therefore, whenever the platoon needs to move from VLC to RF, it switches, and then the packet will be transmitted. The recall is most used when we want to capture positives possibilities.

However, precision presents the proportion of prediction correctly. It is used when we want to be sure of our prediction, which is our main goal.

$$Precision = \frac{TP}{TP+FP} \quad (2)$$

where  $(TP + FP)$ : number of positive samples

F1-measure is a metric that combines recall and precision by taking their harmonic mean. It is used for good recall and precision. Where:

$$F1 - measure = \frac{2 \times Recall \times Precision}{Recall + Precision} \quad (3)$$

### 7.2.3.3 Log Loss Metric

Log Loss metric measures the performance of models where the prediction input is a probability value between 0 and 1. The Log loss increases as the predicted probability diverge from the actual label.

$$The \ Log \ Loss: L(\pi) = -\log(\pi) \quad (4)$$

where  $\pi$  is the probability of the real class. In general, minimizing Log Loss results in higher accuracy for the classifier.

### 7.2.3.4 AUC ROC

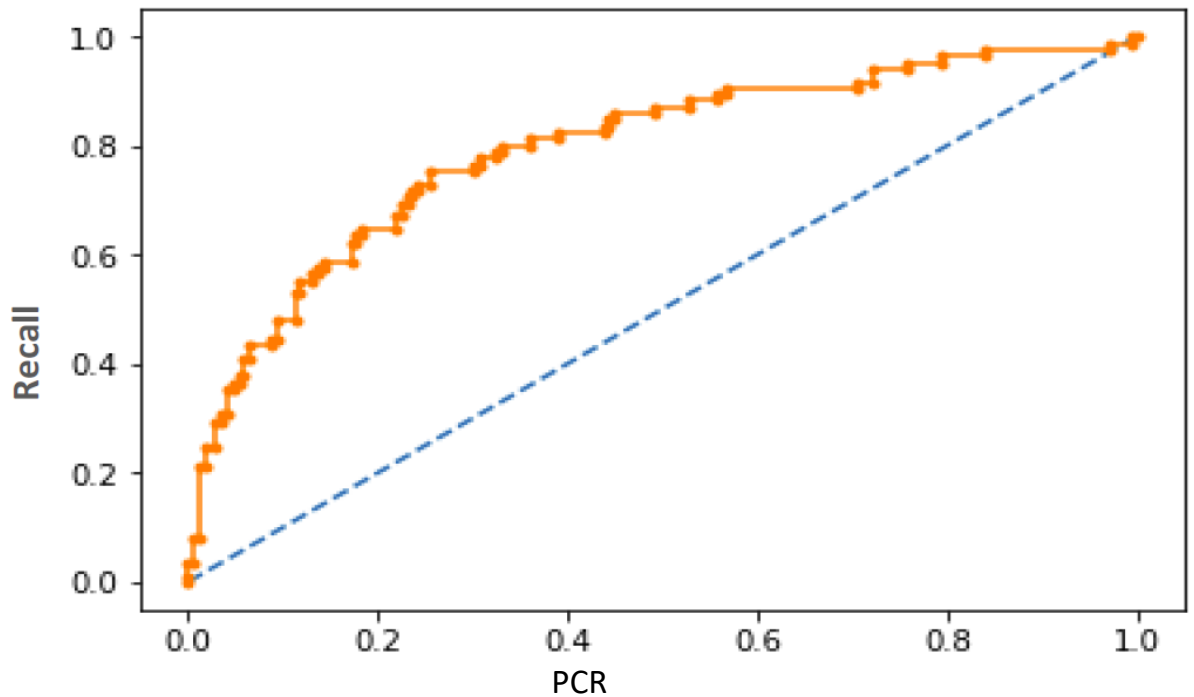


Figure 7.18: ROC with AUC = 79.55%

AUC is the area under the ROC curve. This method separates the probability of positive classes from the negative ones. It is noteworthy that AUC ROC is used for probabilistic classifiers.

ROC results via plotting recall in the function of false-positive rate (FPR) as we can see in figure 7.18 where:

$$FPR = \frac{FP}{TN+FP} \quad (5) \quad \text{The proportion of false captured by the model}$$

A perfect classifier will have the ROC curve along the Y-axis and then along the X-axis. In our ML, the KNN and SVM are discriminative classifiers that should use a probabilistic framework [163]. However, the decision tree and random forest give an estimation of probability [164]. According to this probability, we evaluated the performance of the decision tree and random forest modelling via Log Loss and AUC ROC.

### 7.2.3.5 Matthews Correlation Coefficient (MCC)

Similar to F1 measure, MCC is a single-value metric that summarizes the confusion matrix; MCC takes into account all four entries of the confusion matrix:

$$MCC = \frac{TN \times TP - FP \times FN}{\sqrt{(TN+FN)(FP+TP)(TN+FP)(FN+TP)}} \quad (6)$$

“MCC is high only if your classifier is doing well on both the negative and the positive elements,” states Davide Chicco in [165]. The MCC allows the identification of the classifier's inefficiency in classification, especially of negative class samples. It is helpful in our case that aims to transmit without interruption.

- **Scenario 1:**

Table 7.9: Classification metrics (Scenario 1)

Model \ Metric	SVM	KNN	Decision Tree	Random Forest
<b>Accuracy</b>	Linear: 0.7071 RBF: 0.7214	0.997619	0.985714	0.997619
<b>Confusion Matrix</b>	[[187 30] [ 72 131]]	[[216 4] [ 0 200]]	[[216 1] [ 7 196]]	[[207 1] [ 1 211]]
<b>F1-Measure</b>	Linear: 0.72 RBF: 0.76	0.99	0.98	1.00
<b>Log Loss</b>			0.657894	0.164472
<b>AUC ROC</b>			0.980528	0.995237
<b>MCC</b>	0..0	0.995247	0.962220	0.990475

All classification metrics confirm that the Random Forest is better than the decision tree in terms of performance and good prediction of positive and negative samples, where random forest has lower Log Loss than decision Tree.

The random forest, KNN perform accurately. The random forest is considered better than KNN by using the F1-Measure technique. Therefore, KNN performs slightly better on both positive and negative elements, and the random forest is considered the most accurate model.

- **Scenario 2:**

Table 7.10: Classification metrics (Scenario 2)

Model \ Metric	SVM	KNN	Decision Tree	Random Forest
<b>Accuracy</b>	Linear: 0.6666 RBF: 0.6466	0.8333	1.0	0.85-0.993
<b>Confusion Matrix</b>	Linear: [[97 0] [ 5 48]] RBF: [[97 0] [53 0]]	[[100 1] [24 25]]	[[63 0] [ 0 87]]	Random
<b>F1-Measure</b>	Linear: 0.97 RBF: 0.51	0.82	1.0	0.86-0.99
<b>Log Loss</b>			9.99e- 16	0.23-5.06
<b>AUC ROC</b>			1.0	0.834- 0.995
<b>MCC</b>	Linear: 0.928 RBF: 0.0	0.619	1.0	0.64- 0.986

Decision tree, random forest and linear SVM perform accurately. No doubt that decision tree is the best algorithm in terms of all metrics. However, as we interpret the tree of scenario 2, the tree has just one split. Therefore, we are not able to trust the decision tree for new samples.

Hence, we devise and adopt the random forest to make decisions on VLC communication within the platoon during the day.

## 7.3 Network selection

The VLC platoon performance study shows that QoS parameters are highly affected by vehicular traffic. The degradation of VLC quality of service occurs when the vehicular traffic reaches a threshold that is relative to each of the four cases: high density, medium density, low density and sparse traffic.

Vertical handover execution is urged with critical safety packets that require to be transmitted in a right time window. In our study, we tackle the collision warning application that falls into the category of critical real-time active safety. Our research work devises a handover decision module that is based on a sigmoid utility function. The latter is used to select the suitable candidate RF technology: 802.11p, LTE-V.

### 7.3.1 Utility function

Each platoon leader will calculate the sigmoid utility function for each technology. Thus, the RF technology that induces the greatest utility is the platoon's candidate technology.

We assume the adopted criterion is  $(x_k)$ . Those that affect network selections are: delay  $(x_1)$  and data rate  $(x_2)$ . The selected application has a lower bound  $(x_\alpha)$  and a higher bound  $(x_\beta)$ . Moreover, every criterion assumes  $(x_m)$  value that represents the threshold value between satisfied and unsatisfied zones. The sigmoid utility function for each criteria  $x_k$  and each network  $n$  is then computed as follows:

$$u_n(x_k) = \begin{cases} 0 & \text{if } x_k < x_\alpha \\ \frac{\left(\frac{x_k-x_\alpha}{x_m-x_\alpha}\right)^\xi}{1+\left(\frac{x_k-x_\alpha}{x_m-x_\alpha}\right)^\xi} & \text{if } x_\alpha \leq x_k \leq x_m \\ 1 - \frac{\left(\frac{x_k-x_\alpha}{x_\beta-x_m}\right)^\gamma}{1+\left(\frac{x_k-x_\alpha}{x_\beta-x_m}\right)^\gamma} & \text{if } x_m < x_k \leq x_\beta \\ 1 & \text{if } x_k > x_\beta \end{cases} \quad (7)$$

Where the values of  $\xi$  and  $\gamma$  determine the steepness of the utility and allow modeling the user's sensibility to access network variation characteristics.

$$\gamma = \frac{\xi(x_\beta - x_m)}{x_m - x_\alpha}$$

$$\xi \geq \max\left(\frac{2(x_m - x_\alpha)}{(x_\beta - x_m)}, 2\right)$$

The platoon leading vehicle calculates the utility function relative to two access technologies: 802.11p and LTE-V ( $n=2$ ). The global utility relative to an application in a network  $n$ , is then:

$$U_n = \prod_k u_n(x_k)^{w_{kn}} \quad (8)$$

Where  $x_{kn}$  is the weighting factor for delay and data rate. The weighting factor value indicates the level of importance of the criterion in an application; it varies from one application to another. For instance, some applications have a low need for high data throughput but require high latency requirements; in such cases, greater weight should be given to the delay criterion.

### 7.3.1.1 Simulation parameters

In an attempt to validate the proposed vertical handover performance, we conducted a set of simulation batches using OMNET and SUMO. We adopted the scenario illustrated in Figure 1. A vehicular platoon disseminates collision warning messages on VLC. The platoon moves on a 2-lane highway of 2Km, served by two eNodeB LTE-V and 10 RSU. The transmission range of the eNodeBs is 1 km and 300 m for each RSU. Disruptive vehicles arrive according to the distribution model relative to the four cases previously described.

Table 7.11 indicates the limit and threshold for every utility criterion (delay and data rate) for PDA packets previously described. Moreover, we assume an added weight ( $\alpha=0.6$ ) that ensures the quality of service [166].

Table 7.11: QoS boundary and the threshold for the collision warning application [162]

V2X application	Delay (ms)				Data rate (Mbps)			
	$x_\alpha$	$x_m$	$x_\beta$	$w_1$	$x_\alpha$	$x_m$	$x_\beta$	$w_2$
PDA	0.3	0.6	1	0.6	4	6	10	0.4

### 7.3.1.2 Performance analysis

To validate the vertical handover, we evaluate the failure probability as a function of disruptive vehicles for the 4 cases described in the previous chapter as illustrated in figure 7.19.

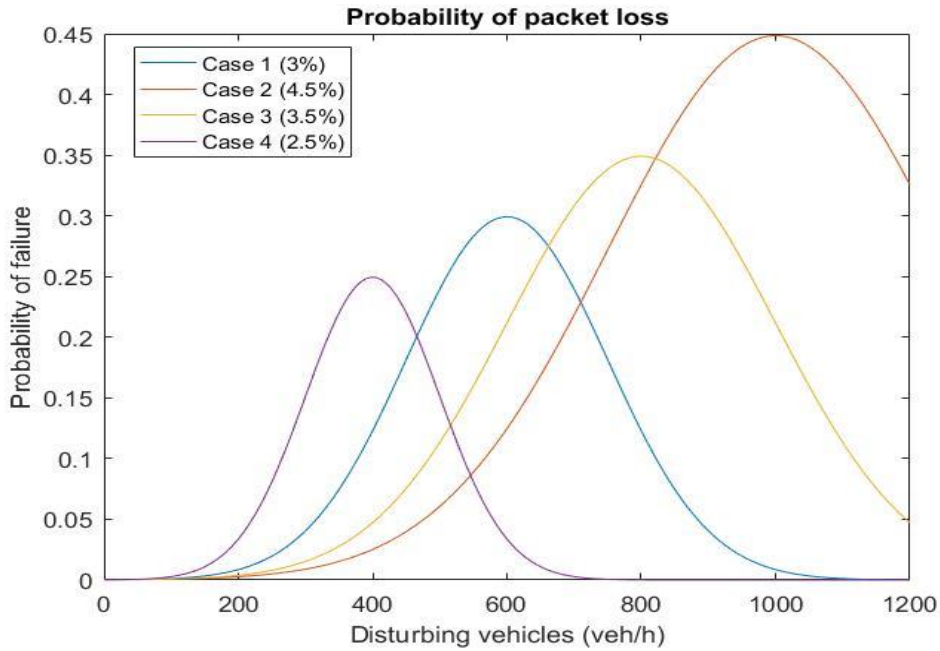


Figure 7.19: Packet probability of failure

The probability of failure is done according to the threshold value: the higher the threshold value is, the higher the probability of failure reach. Moreover, the probability of failure increases with the arrival rate of disruptive vehicles; it reaches a peak value of 3, 4.5, 3.5 and 2.5 respectively for cases 1, 2, 3 and 4 and decreases gradually after reaching the threshold value in each case.

Figure 7.20 illustrates the packet retransmission delay after re-execution of vertical handover from VLC to a radio frequency technology (802.11p and LTE-V) as a function of packet size. It is noteworthy that the packet is retransmitted due to a transmission failure with VLC.

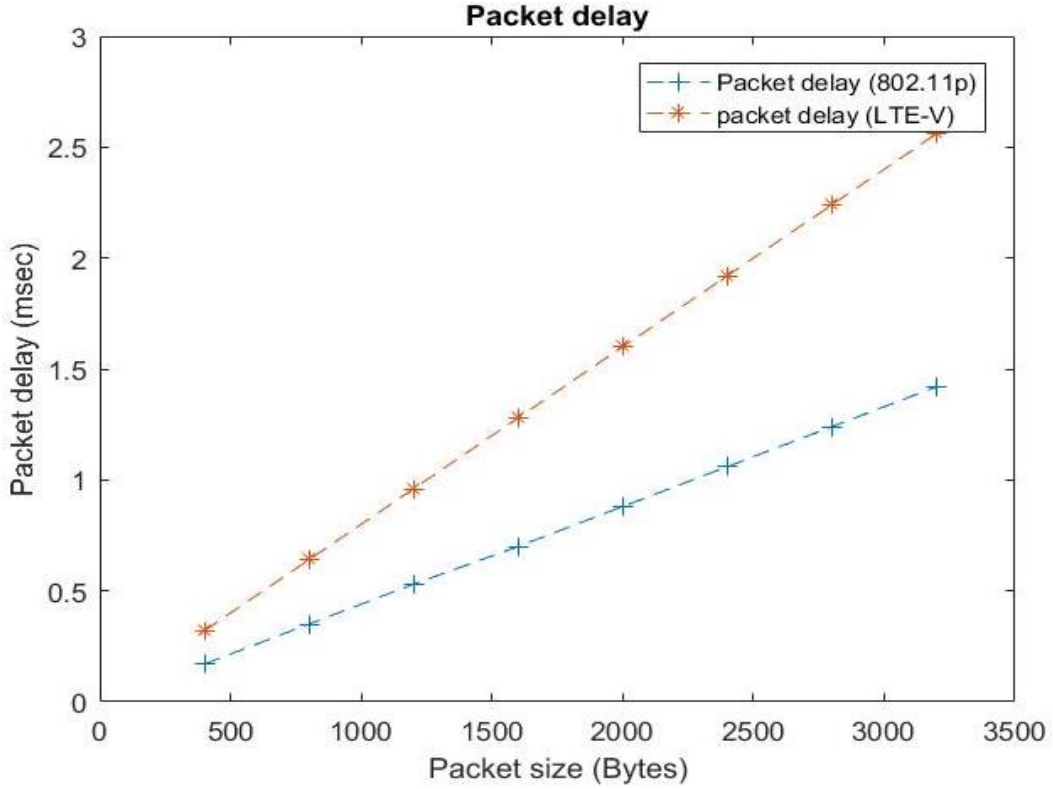


Figure 7.20: Packet delay after VHO

It is obvious that the packet delay increases with the packet size increase. In both cases, the packet delay of 802.11p technology is lower than that of LTE-V technology since the throughput of 802.11p technology is higher than LTE-V technology in V2V communication.

### 7.3.2 Cooperative Game for Network Selection

All games are categorized as cooperative and non-cooperative. In cooperative games, the main objective is the global outcome obtained from player combinations. In non-cooperative games, each player is processed independently and all possible outcomes are studied. The game is played among groups of players in the first case and among individual players in the second case.

In this section, we propose a cooperative game to prevent network overloading and reduce unnecessary handover transitions. This game has three main components: players, strategies and utilities. The players of this game are the  $n$  platoons of the network named by  $\{1,2,\dots,n\}$ . Each platoon leader adopts a specific strategy, denoted by  $\{s_1,s_2,\dots,s_n\}$ , where  $s_i$  is the selection ratio for  $i$ . The total utility of the cooperative game is defined as:

$$R_{\text{total}}(s_1,s_2,\dots,s_n) = \sum_{i=1}^n (Q_i - c_i) s_i \quad (9)$$

Where  $Q_i = 1 - \frac{L_i}{L_{th}}$ ,  $L_i$  is the current load of network  $i$ ,  $L_{th}$  is the predefined load threshold of network  $i$  (maximal acceptable load), and  $c_i$  is a cost weight paid by network  $i$ .



The primary objective of the cooperative game is to determine the strategies that optimize the utility function for each network. In fact, it is more appropriate to provide a high selection ratio to the most uncongested network. However, this can lead to an unbalanced allocation between networks and reduce the probability of selecting a certain set of networks.

In addition, allocating a selection ratio to a network based only on its charge, can result in inappropriate selections. For this purpose, each network should charge a cost based on the amount of time  $t_i$  spent by a vehicle in its cell.  $t_i$  is affected by the maximum speed of the vehicle, the cell radius of the target network and the path travelled by the vehicle.  $t_i$  is computed using the method proposed in [167]. Consequently, the penalty weight is determined as follows:

$$c_i(t_i) = \begin{cases} 1 - \frac{t_i}{t_{th}} & \text{if } t_i < t_{th} \\ 0 & \text{if } t_i > t_{th} \end{cases} \quad (10)$$

Where  $t_{th}$  is a defined by the threshold time (the time needed for a vehicle in a cell without performing an unnecessary handover). The game can be formulated as follows:

$$\begin{aligned} \max_{s_i} \quad & R_{total}(s_1, s_2, \dots, s_n) \\ \text{s.t.} \quad & \sum s_i = 1 \\ & s_i \geq 0 \quad \forall i \in n \end{aligned} \quad (11)$$

The target network selection module makes the final decision. The goal of this module is to ensure that the application is assigned to a suitable network with the highest utility calculated and the highest selection ratio:

$$N_{targeti} = \max[U_i \times S_i] \quad (12)$$

The selected network  $N$  is the multiplication between the utility function and the selection ratio of each network. The network with the highest  $N$  is the selected network (target network  $i$  that has the maximum combination of utility and selection ratio for the application).

### 7.3.2.1 Simulation parameters

Vehicle platoons are covered by two existing technologies access points: Roadside Units and eNodeBs which provide respectively 802.11p and LTE-V wireless access. This network is implemented using the Objective Modular Network Testbed in C++ (omnet++) and the Simulator for Urban Mobility 0.32.0 (SUMO).

We worked with 100 platoons on a map size of  $3 \times 2 \text{ km}^2$  that is covered by 3 LTE-V eNodeBs and 15 RSUs. The radio transmission range of each eNodeB is 1km respectively to 300 m for each RSU. Each platoon leader is responsible for computing the selection ratio related to each network. The network with the highest selection ratio is the one that is picked. This selection ratio is affected by four essential parameters:

- L1 the current load of 802.11p
- L2 the current load of LTE-V
- t1 the time spent by the vehicle in 802.11p cell
- t2 the time spent by the vehicle in LTE-V cell

### 7.3.2.2 Performance analysis

Figure 7.21 and 7.22 illustrate the unnecessary HO request and packet loss ratio for QoS-VH and the selection ratio algorithm for both technology (LTE-V and 802.11p). Our selection ratio algorithm is based on the cooperative game; however, the quality of service vertical handover technique (QoS-VH) is based on the maximum effective data receiving rate as network selection metric.

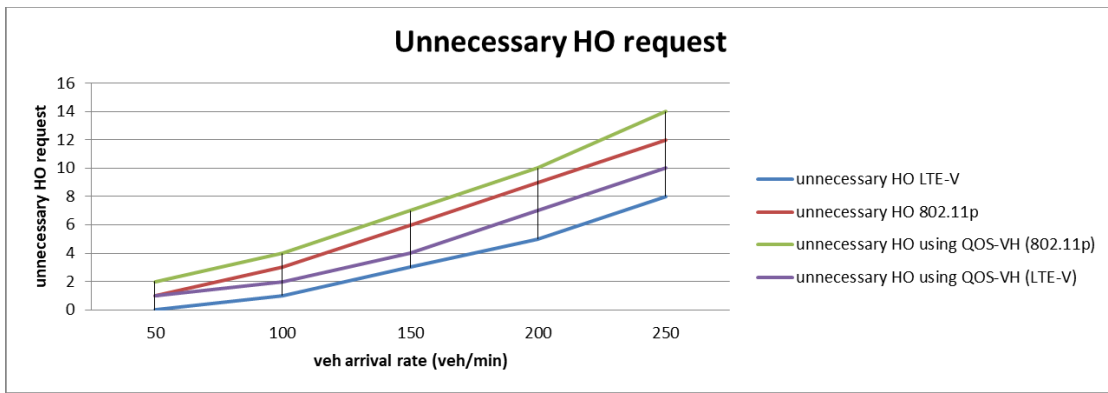


Figure 7.21: Unnecessary HO request for QoS-VH and selection ratio algorithm

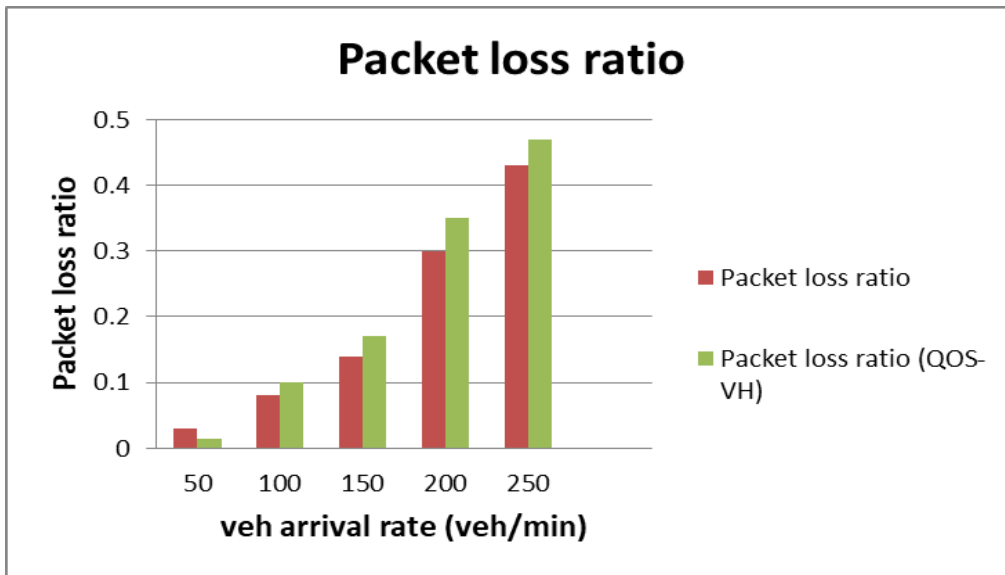


Figure 7.22: Packet loss ratio for QoS-VH and selection ratio algorithm

By Using the QoS-VH technique, whenever users need to trigger vertical handoffs, they will compute QoS parameters (effective data rate).

Comparing between the QoS-VH and our selection ratio algorithm, the unnecessary HO request and the packet loss ratio increase by increasing the vehicle arrival rate. By using our algorithm we will have less unneeded request for HO and less packet loss ratio for both RF technologies because the network selection using QoS-VH is based on the maximum effective data received and neglects the network delay. However, in our selection ratio algorithm, we take into consideration both criteria ( the time spent in each network and the data rate).

Figure 7.23 presents the access delay to the 802.11p and LTE-V after HO in both methods.

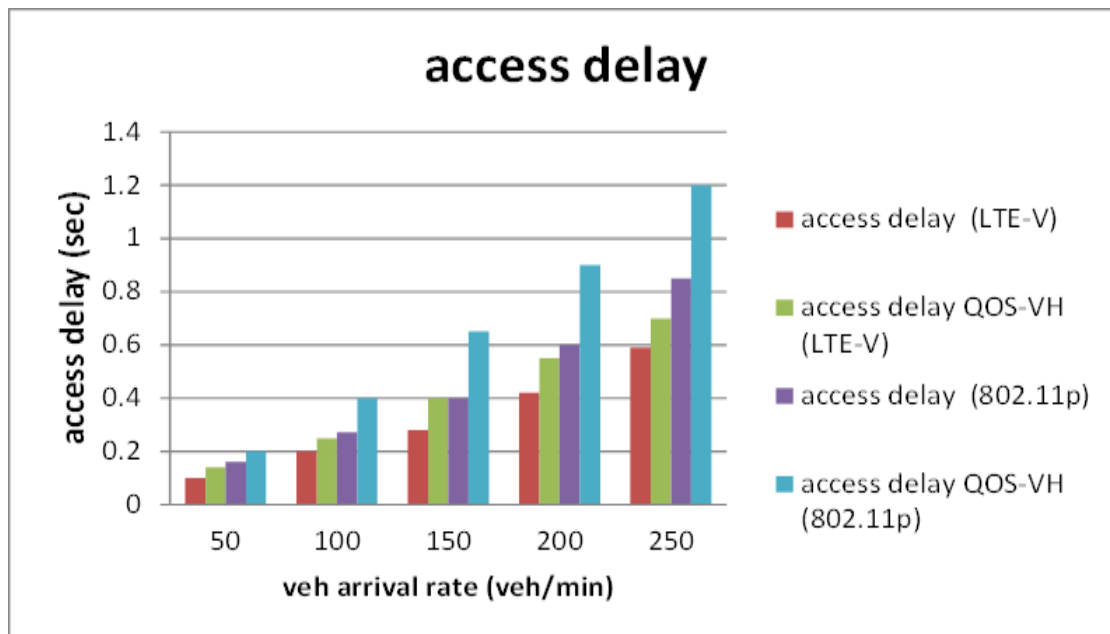


Figure 7.23: Access delay of 802.11p and LTE-V using QoS-VH and selection ratio technique

Concerning both methods, the access delay will increase by increasing the vehicle arrival rate. Comparing the two methods, the access delay after HO by using our algorithm is less than the QoS-VH technique. The network selection using QoS-VH is based on timing strategy which is considered an inappropriate technique for V2V use cases.

## 7.4 Conclusion

Safety messages are considered as primary messages in the vehicle network; therefore, any delay of this message may affect vehicle safety. For this reason, QoS degradation must be tackled with an effective solution in order to transmit messages without any latency.

VHO is seen as a solution to QoS degradation problems. The crucial step in VHO is the HO decision, where we used the threshold value and the machine learning technique (KNN, SVM, decision tree and random forest).

Furthermore, the switch from VLC to RF technology should be done efficiently with direct access to the chosen technology and must enhance the QoS in order to receive the message without any delay. The chosen techniques are the utility function and the selection ratio. These techniques improve the packet loss ratio and reduce the number of unneeded HO request.

## 8. Chapter 8: Conclusion

### 8.1 Contributions Summary

Intelligent Transport Systems offer transport solutions by adopting innovative cooperative infrastructure, smart vehicles and advanced wireless technologies. ITS contributes to improve road safety, efficiency and comfort, as well as environmental conservation through enabling smoother traffic by relieving traffic congestion.

Several types of wireless communication technologies have been proposed for intelligent transport systems. Short-range communications can be achieved using IEEE 802.11 protocols or VLC which is based on the LED implemented in vehicles. Theoretically, the coverage of these technologies can be achieved by using mobile ad hoc networks or mesh networks. Longer range communications have been proposed using infrastructure networks such as LTE-V, WiMAX (IEEE 802.16), or 4G.

In order to elucidate various aspects of ITS, different user services and technologies are needed to emphasize the need for developing national ITS strategies.

This thesis was mainly concerned with the evaluation of the benefits of VLC technology. More specifically, we elucidate various aspects of VLC performance and emphasize the need for complementing VLC with RF technologies when the degradation level is reached. This study was elaborated in the context of vehicular platooning that organizes traffic in groups of close-following vehicles.

At the first step, we designed a platoon formation algorithm called SPS:

1. A new platoon formation algorithm called "speed platoon splitting" (SPS), has been developed and evaluated to arrange the vehicles to form platoons at the entrance ramp.
2. The SPS algorithm considers two main factors which have a significant impact on the performance of our algorithm: velocity and traffic congestion.

We considered a highway with two different lanes; each platoon should choose the appropriate lane. The first lane is reserved for vehicles with high speed (vehicles with low speed will be obligated to speed up) and the second one is reserved for vehicles with low speed (high-speed vehicles should slow down).

Traffic congestion is considered an essential issue that should be solved. The majority of platoon formation algorithms in the literature do not take vehicular density and congestion into consideration. Indeed, traffic congestion occurs when vehicular density exceeds highway capacity. In our algorithm, we consider that each highway entrance is equipped with a ticket pool that controls the volume of vehicle traffic entering the road by applying preventive congestion control.

3. Our SPS algorithm maximizes the platoon lifetime by choosing the position of vehicles in the platoon according to their destination where the leader vehicle has the farthest destination and the last vehicle has the nearest destination. SPS integrates a ticket pool mechanism that regulates vehicular flow by controlling inter-platoon spacing.

At a second step, we evaluated the impact of vehicular perturbation on VLC performance parameters:

1. We evaluated the performance of a platoon of cars in the presence of disturbing vehicles. The study was evaluated with a multi-class non-preemptive priority mathematical modeling. The mathematical results are validated with simulation. We evaluated the usable throughput, probability of failure, activity period of disturbing vehicles, virtual packet service time and Probability of K consecutive disturbances followed by success.
2. We have a special concern to cooperative awareness application executed in a platoon where we propose the Platoon Driving Assistance (PDA) application, based on the Cooperative Awareness Messaging (CAM) standard. We identified four cases that capture four levels of vehicular densities, spanning from high traffic density to sparse traffic density where vehicular platoons move on a dedicated lane sending urgent messages and disturbing vehicles travel on the neighbouring lane. We performed a mathematical model based on M/GI/1 multiclass queuing model (with two classes of service) which adopts a non-preemptive priority policy for each class of service. This mathematical model is validated by an authentic simulation to determine the mean time of platoon disturbance and the percentage of packet loss.

At a third step, we devised a vertical handover strategy that enables the switch from VLC and RF communications to enhance the network performance. In order to overcome VLC failures, data transmission has to be done continuously using backup technologies, which ensure the overall quality of service of the system, and maximise the safety of autonomous driving.

1. The vertical HO decision is devised by machine learning algorithms. We tackle two cases: the first case is related to interference caused by disturbing vehicles at night. The second case focuses on sun interference.
  - The vertical handover is triggered when QoS degradation thresholds are reached. The threshold values are calculated based on the average percentage loss of packets in each case which differ from one case to another. Whenever the threshold value is reached, a vertical handover is triggered to switch critical messages transmission to the RF technology.
  - The decision of the best wireless technology candidate is taken based on the adoption of machine learning algorithms. We analyze data before to be fed into Machine Learning algorithms in order to devise platoon for the right technology either wireless or visible light. These ML algorithms, namely K-Nearest Neighbor, Support Vector Machine, Random Forest, Decision Tree and Ensemble voting train the model based on a set of training data and focus on predicting transmission success within platoons' vehicles.

- A comparison of performance between the different ML algorithms through several metrics, namely Confusion Matrix, F1-Measure, Log Loss Metric, AUC ROC and MCC confirm that Random Forest is better than the decision tree in terms of performance and good prediction of positive and negative samples. In the two cases, Random forest was set as a very accurate model.
2. We proposed to switch the VLC technology to a RF technology based on an innovative utility function coupled with a cooperative game theory.
- In our study, we tackled the collision warning application that falls into the category of critical real-time active safety. Our research work devises a handover decision module that is based on a sigmoid utility function where each platoon leader will calculate the sigmoid utility function for each technology. Thus, the RF technology that induces the greatest utility is the platoon's candidate technology. To validate the vertical handover, we evaluated the failure probability as a function of disturbing vehicles.
  - In the second technique, a cooperative game is proposed to prevent network overloading and reduce unnecessary handover transitions. The primary objective of the cooperative game is to determine the strategies that optimize the utility function for each network where the technology that provides a high selection ratio is the most uncongested network.

## 8.2 Future Perspective

This thesis opens the road to various research axes. Our future perspectives are listed below:

- One of our future perspectives is allowing each vehicle to make its own decision. At each interval of time, each vehicle in the platoon will select its appropriate technology keeping the VLC or switching to the RF technology (802.11p or LTE-V) according to specific criteria based on real-time learning.
- After VHO, the vehicles in the platoon will use the RF technologies according to the different techniques used as mentioned in chapter 7 and each vehicle will drive alone on the highway. Our future work will focus on regrouping the platoon and reusing the VLC after a specific study of performance parameters.
- Concerning the static threshold value mentioned in chapter 7, an enhancement should be done to this method. In fact, a dynamic threshold value should be adopted for all cases in the future.
- A study performance of different forms of environmental interference (snow, fog) and a study of the performance of VLCs in the presence of these types of

interference. Using machine learning to make VHO decision and then testing a new approach to select among the different types of RF technologies.

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