Universidade de Aveiro Departamento de Eletrónica, Telecomunicações e Informática
Ano 2019

Nuno Fábio Gomes Camacho Ferreira

Controlo de Acesso ao Meio em Comunicações Veiculares de Tempo-Real

Medium Access Control in Real-Time Vehicular Communications

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Tese apresentada à Universidade de Aveiro para cumprimento dos requisitos necessários à obtenção do grau de Doutor em Engenharia Eletrotécnica.

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Dedico este trabalho à minha esposa, Mónica, ao meu filho, Guilherme, à minha mãe, Paulina, e à minha sogra Filomena, que estará sempre comigo.

o júri

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palavras-chave

Controlo de Acesso ao Meio (MAC), Ambientes Veiculares, Comunicações Tempo-Real, IEEE 802.11p / WAVE, Infra-Estrutura.

resumo

Apesar de diversas medidas preventivas, o número de acidentes rodoviários continua a ser muito elevado, sendo mesmo considerado uma questão de saúde pública por algumas entidades. Esta tese tem como objetivo geral contribuir para a redução desse número de acidentes, e consequentes fatalidades, através da utilização de aplicações de segurança que envolvem comunicação entre veículos. Em particular, o objetivo principal é garantir que a comunicação entre utentes, em ambientes veiculares, seja efetuada com limites temporais apropriados à transferência de informações críticas. De forma mais detalhada, é estudada a gestão do escalonamento das transmissões (controlo de acesso ao meio – MAC) que irá definir quem vai comunicar e quando o pode fazer. São estudadas situações (desejadas) onde há uma infra-estrutura de comunicações com cobertura integral (RSUs), a partir da qual se faz a coordenação do acesso ao meio pelos veículos (OBUs), e situações (esporádicas, por ausência de RSU) em que a rede de comunicação é "ad hoc" e apenas constituída pelos veículos presentes. Utiliza-se a recente norma WAVE / IEEE 802.11p, específica para comunicações veiculares, e propõe-se uma solução baseada em TDMA, com coordenação apropriada entre RSUs para disseminação efetiva de um evento crítico de segurança. A escolha do instante para o *broadcast* inicial do evento de segurança também é tida em conta, e são comparados dois casos distintos. No caso da ausência de infraestrutura, derivam-se métodos para minimizar colisões no acesso ao meio de comunicação, e maximizar a largura de banda disponível. Os resultados refletem o atraso total *end-to-end*, mostrando tempos apropriados para os requisitos das aplicações em causa, e evidenciando melhorias aquando da escolha alternativa para o instante do *broadcast* inicial.

keywords

Medium Access Control (MAC), Vehicular Environments, Real-Time Communications, IEEE 802.11p / WAVE, Infrastructure.

abstract

Despite several preventive measures, the number of roadway accidents is still very high, being considered even a problem of public health by some entities. This thesis has as global purpose of contributing to the reduction of that number of accidents, and consequent fatalities, by using safety-related applications that use communication among vehicles. In particular, the primary goal is guaranteeing that communication between users in vehicular environments is done with appropriate time bounds to transfer safety-critical information. In detail, it is studied how to manage the scheduling of message's transmissions (medium access control - MAC), in order to define precisely who will communicate and when is the appropriate instant. The preferable situation where a communication infrastructure is present with full coverage (RSUs) is also studied, from which medium access control is defined precisely, and vehicles (OBUs) become aware of medium utilization. Also, sporadic situations (e.g., absence of RSUs) are studied in which the communication network is "ad hoc" and solely formed by the current vehicles. It is used the recently WAVE / IEEE 802.11p standard, specific for vehicular communications, and it is proposed a TDMA based solution, with appropriate coordination between RSUs in order to effectively disseminate a critical safety event. It is taken into account two different ways of choosing the instant for the initial broadcast, and both cases are compared. In case there is no infrastructure available, methods are derived to minimize communication medium access collisions, and to maximize the available bandwidth. The results reflect the total end-to-end delay, and show that adequate times are attained, and meet with the requisites for the type of applications being considered. Also, enhancements are obtained when using the alternate choice for the initial broadcast instant.

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

LIST OF ABBREVIATIONS

AC	Access Category
ACI	Access Category Index
ACK	Acknowledgment
AFR	Asynchronous Fixed Repetition
AFR-CS	Asynchronous Fixed Repetition with Carrier Sensing
AIFS	Arbitration Inter-Frame Space
AIFSN	AIFS number
AP	Access Point
APR	Asynchronous p-persistent Repetition
APR-CS	Asynchronous p-persistent Repetition with Carrier Sensing
ARQ	Automatic Repeat-reQuest
AU	Application Unit
BSS	Basic Service Sets
CAH-MAC	Cooperative ADHOC MAC
CAI	Common air interface
CAM	Cooperative Awareness Message
CCH	Control Channel
CDMA	Code Division Multiple Access
CFCW	Cooperative Forward Collision Warning
CP	Contention Period
CSMA	Carrier Sense Multiple Access
CTS	Clear-to-send
CW	Contention Window
C2C	Car-to-Car
C2C-CC	Car-to-Car Communication Consortium
DCF	Distributed Coordination Function
DENM	Decentralized Environmental Notification Message
DHRP	Direction based Hazard Routing Protocol

DIFS	Distributed Inter-frame Spacing
DSRC	Dedicated Short-Range Communications
EDCA	Enhanced Distributed Channel Access
EEBL	Emergency Electronic Brake Lights
ETSI	European Telecommunications Standards Institute
EP	Event Period
FCC	Federal Communication Commission
FDD	Frequency division duplexing
FDMA	Frequency Division Multiple Access
FI	Frame Information
GH	Group Header
GI	Guard Interval
GN	Group Nodes
GSM	Global System for Mobile Communications
GPRS	General Packet Radio Service
HB	Heartbeat
HSPA	High Speed Packet Access
ICT	Information and Communication Technologies
IDM	Intelligent Driver Model
IEEE	Institute of Electrical and Electronics Engineers
InfP	Infrastructure Period
IP	Internet Protocol
ISM	Industrial, scientific and medical
ISO	International Organization for Standardization
ITS	Intelligent Transportation Systems
I2I	Infrastructure-to-Infrastructure
I2V	Infrastructure-to-Vehicle
LLC	Logical Link Control
LPG	Local Peer Groups
LTE	Long Term Evolution
MAC	Medium Access Control
MACA	Multiple Access Collision Avoidance

MACAW	Media Access Protocol for Wireless LANs
MANET	Mobile Ad Hoc Network
MBMS	Multimedia Broadcast/Multimedia Services
NAV	Network Allocation Vector
NS	Normal Slots
OBD2	On Board Diagnostics II
OBU	On-board unit
OFDM	Orthogonal Frequency Division Multiplexing
OSI	Open Systems Interconnection
PAN	Personal Area Network
PCF	Point Coordination Function
PIFS	Point Inter-frame Spacing
PTT	Push-To-Talk
QoS	Quality of Service
RAMC	RSU-Assisted Multi-channel Coordination
RFID	Radio-Frequency IDentification
RTS	Request-to-send
RSU	Road-side unit
SCH	Service Channel
SFR	Synchronous Fixed Repetition
SIFS	Short Inter-frame Spacing
SloP	Slotted Period
SMS	Short message service
SPR	Synchronous p-persistent Repetition
STDMA	Self-Organized Time Division Multiple Access
TCP	Transmission Control Protocol
TDD	Time division duplexing
TDMA	Time division multiple access
UDP	User Datagram Protocol
UMTS	Universal Mobile Telecommunications System
UTC	Coordinated Universal Time
VANET	Vehicle Ad Hoc Network

VCN	Vehicular Communication Network
VoIP	Voice over Internet Protocol
V2I	Vehicle-to-Infrastructure
V2V	Vehicle-to-Vehicle
V2X	Vehicle-to-Everything
WAVE	Wireless Access in Vehicular Environments
WBSS	WAVE Basic Service Set
WINA	Wireless Industrial Networking Alliance
WMP	Warning Message
WSA	WAVE Service Advertisement
WSM	WAVE Short Message
WSMP	WAVE Short Message Protocol
3GPP	3rd Generation Partnership Project

LIST OF VARIABLES

$C_{dE}(t_1)$	Set of vehicles within the distance of interest of event $E(t_1)$
c_g	Event generating vehicle
c_{length}	Vehicle average length
$c_{spacing}$	Inter-vehicle separation gap
d_{cr}	RSU coverage range (radius)
d_{mt}	Message target distance
D_{rl}	Road length
f_i	Vehicle direction information
$InfP_{slot}$	Infrastructure Period slot chosen for beacon transmission by a RSU
$lane_{nr}$	Lane number where the vehicle is travelling
n_{c_max}	Maximum number of vehicles at the range (radius) of a specific RSU
$n_{c\_one\_slot}$	Number of vehicles within one slot
n_{dE}	Number of vehicles within the distance of interest of an event
n_{lanes}	Number of highway lanes in each direction
n_{ret}	Number of retransmissions to be done by the RSU eligible for rebroadcast
n_{td}	Number of rebroadcasts for safety message dissemination
p_{coll}	Collision probability (at least two OBUs transmit a packet)
p_{collf}	Final collision probability (at least two OBUs transmit a packet and choose the same slot)
p_{free_r}	Probability of all vehicles choosing a different slot randomly
p_{same_slot}	Probability that at least two OBUs choose the same SloP slot for transmission
$p_{same\_slot\_d}$	Probability that at least two OBUs choose the same slot deterministically
$p_{same\_slot\_r}$	Probability that at least two OBUs choose the same slot randomly
p_{tx}	Transmission probability
Q	Expected number of packets waiting in the highest priority transmitter queue
RSU_{ax}	Adjacent RSU (being x "l" or "r" to denote left or right, respectively)
RSU_{nr}	RSU unique number according to its position along the road

$\boldsymbol{RSU_p}$	Primary RSU
$\boldsymbol{Section_{nr}}$	Section number where the RSU is located within the road
$\boldsymbol{SloP(CP)}$	Number of slots that are available for vehicles within the Slotted Period
$\boldsymbol{slot_{1lane}}$	Slot chosen for vehicle broadcast within the Slotted Period on one lane (per side) roads
$\boldsymbol{t_{lf}}$	Message lifetime
$\boldsymbol{t_m}$	Medium access delay
$\boldsymbol{t_{m\_bc}}$	Medium access delay for the best-case scenario
$\boldsymbol{t_{m\_wc}}$	Medium access delay for the worst-case scenario
$\boldsymbol{t_q}$	Queuing delay
$\boldsymbol{W}$	Backoff window size
$\boldsymbol{x_{Ci}(t)}$	Vehicle's position at instant *t*
$\boldsymbol{x_{RSUb}}$	Position of RSU behind the vehicle
$\boldsymbol{\lambda}$	Birth rate of an M/G/1 queue (packets/second)
$\boldsymbol{\rho}$	Percentage of time in which there is a packet in the server of an M/G/1 queue
$\boldsymbol{\sigma_{tm}}$	Standard deviation of the medium access delay

CHAPTER 1

INTRODUCTION

Summary

Vehicular networks are an emergent field of research and applications. Using wireless communications in those networks offers a wide range of possibilities, but at the same time poses demands in terms of bounded delay, particularly in safety-related applications. This work investigates the efficiency of MAC protocols based on IEEE 802.11p/WAVE standard to timely deliver safety messages using an already installed infrastructure. This chapter gives detail of context and motivation. The thesis organization is presented at the end of the chapter.

1.1 Context Scenario

The today's society is becoming more and more user of technology in what we maybe can call a technology-dependent living. In several fields of use, technology aids enhancing our lives with safety, commodity, security and entertainment appliances. In most modern societies, and in an increasingly globalized world, a large range of transportation means are used. Therefore, and since technology is becoming pervasive, it is natural to apply the technology knowledge to those transport means. The application of Information and Communication Technologies (ICT) as well as systems engineering concepts, in order to improve transportation systems, has given origin to a new field often referred as Intelligent Transportation Systems (ITS).

In the last decade we have seen an exponential growth in the use of wireless communications in our everyday lives. They have become ubiquitous, covering several areas which largely transcend the commonly known mobile phones. Going from a simple Wi-Fi Internet access, a ZigBee sensor network, or a Bluetooth car speaker phone, we are nowadays surrounded by and taking advantage from wireless communications.

The world has a vast road network. The top five countries (U.S.A., India, China, Brazil and Canada) with the longest network of roadways all each have over 1,000,000 kilometres. Each of the top three countries has over 70,000 kilometres of highway/expressway networks (ROADTRAFFIC-TECHNOLOGY, 2013). As so, the road traffic in everyday lives is overwhelming.

A current trend regarding the application of wireless communications is the implementation of vehicular communication systems, in the so-called Vehicle Ad Hoc Network (VANET). Dedicated Short-Range Communications (DSRC) is a wireless communication channel/service specifically designed to support infrastructure-to-vehicle (I2V) and vehicle-to-vehicle (V2V) communications, and both the USA and Europe have allocated spectrum in the 5.9 GHz band for ITS use (in this case, vehicular). The range of communication is typically less than 1,000 meters. Usually, a communication network is formed between vehicles and road side units that exchange information. The messages are related both with safety and non-safety applications. Safety applications are those focusing on reducing risk for vehicle drivers, and may include accident and obstacle warning, emergency braking, particularly in hazardous zones. Non-safety applications focus on commodity and infotainment aspects, and may include Internet access, weather information and nearest restaurant information for example. These messages are typically delay tolerant whereas safety applications are delay sensitive. Figure 1-1 shows an example of different types of communication in a typical VANET. Also shown is Intra-Vehicle communication, which may be called secondary or auxiliary communication (e.g., GPS navigation or Sensors for car status) (AL-SULTAN [et al.], 2013).

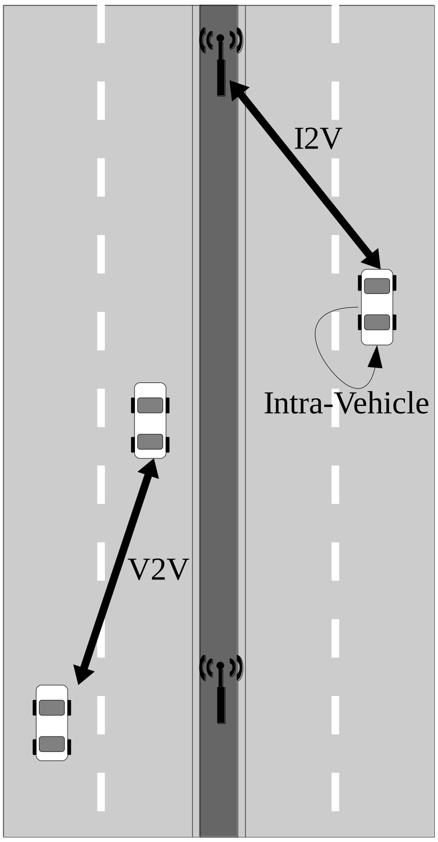

Figure 1-1. Communication types in VANETs.

The focus of this thesis is on improving safety, the prime goal of vehicular communications. Applications falling into that purpose range from intersections approach collision warnings or sudden hard-brake warnings. Considering the applications' specificities and characteristics, certain types have real-time requirements. Within vehicular networks, the information related with safety critical applications is an example of those stringent requirements. For example, a vehicle that breaks suddenly should transmit a warning message, which should be received by other vehicles within a short and bounded period of time; otherwise, there is the risk that such information becomes useless.

1.2 Problem Statement and Motivation

Nowadays, one major concern of all stakeholders (governments, industry and non-government organizations) involved in road traffic management and other traffic related issues, is reducing road injuries and fatalities. To be aware of the importance of such concern, road injuries/fatalities are already considered a public health problem. In a major report jointly issued by the World Health Organization (WHO) and the World Bank, it was highlighted the concern that unsafe road traffic systems are seriously harming global public health and development (PEDEN [et al.], 2004). In this report, projections shown that between 2000 and 2020 road traffic deaths will increase substantially in low to middle-income countries, and without appropriate action, by 2020 road traffic injuries were predicted to be the third leading contributor to the global burden of disease and injury. At the time of the report, more than 3,000 people died every day worldwide from road traffic injuries.

This increasing concern has led the European Union (EU) and USA to the development of vehicular communication standards, namely DSRC, Wireless Access in Vehicular Environments (WAVE), and European Telecommunications Standards Institute (ETSI) ITS-G5. In addition, designing the standards to include infotainment applications that should coexist with the primary safety-related applications, it is possible to enhance the driving experience and extend to the road the constantly connected requirement of today's society.

The recent standards may take into account several aspects such as mobility of vehicular networks, high vehicle's speed, and synchronization to an absolute external time reference. However, even using implementations in conformance with the standards, there are open issues/challenges regarding safety-critical applications. These require typically low channel access delay with a well-defined upper bound. Moreover, in a vehicular network it is possible that an overload situation occurs, where the number of vehicles exceeds largely the resources available. This can be due to using a TDMA based approach, in which the number of vehicles requesting communication exceeds the number of slots available, or also in congested scenarios, even when using a Carrier Sense with Multiple Access (CSMA) approach. In this situation, a "new" vehicle requiring medium access to transmit a safety-critical message should also be able to access the medium within a bounded time.

These challenges are mainly addressed through transmissions scheduling and medium reservation, functions performed in a sub-layer of the OSI model Data Link layer, the Medium Access Control (MAC) layer.

1.3 The Thesis

The thesis argues that an "infrastructure based solution is the most adequate solution at the present to guarantee communication of safety-critical information within appropriate time bounds". The infrastructure is based on full Road Side Units (RSUs) coverage and a time-slotted oriented MAC approach is used. This vision of the solution is taken for the present and near future, taking into account the large design cycle of vehicles, as well as the advantage of an already installed infrastructure at the roads. Besides this, in cases where full RSUs coverage is not available, an alternative solution is envisaged where a pure VANET is used.

In order to accomplish this goal, MAC techniques are proposed to address the identified challenges, by managing transmissions scheduling and defining who should be able to transmit and at what instant.

1.4 Contributions

The goal of timely delivering safety messages, by means of a contention-free or at least a contention-controlled transmission medium, have been addressed mainly in V2V protocols. This PhD work aims to address the same goal but using mainly an I2V approach, which relies in the WAVE standard (and is easily extrapolated for the ITS-G5 standard).

This document is based primarily on work presented in several conferences in the field of this thesis:

- The first contribution was made after researching some WAVE based MAC proposals. By assuming an infrastructure based solution with full RSU coverage, and since the researched MAC protocols did not fully handle the problem of uploading (V2I) safety critical messages, and guaranteeing that such information arrives to the OBU (I2V) within a specified time bound, it was outlined an initial solution based in a slotted approach to the WAVE CCH interval, using RSUs's beacons (Figure 4-1).
- Next, it was developed an alternative solution to overcome the impossibility of using exclusively V2I/I2V communications in some cases. It is considered a

highway where RSUs are only present in particular areas. In the highway areas that are not covered by RSUs, vehicles' safety messages can solely rely on V2V communications for being rebroadcasted.

- Building on the first contribution and detailing it a little more, it was proposed the first guiding lines to beacon coordination between adjacent RSUs, and their safety message retransmission mechanism. Thus, the coordination between RSUs transmitting beacons in the so-called Infrastructure Period, as well as message dissemination (I2V) was further detailed.
- In parallel with the works of this thesis, some work was done in what concerns the MAC layer initial implementation, regarding the development of a WAVE conforming prototype, which was tested successfully in the USA.
- The end-to-end delay performance metric was subject to analysis. This may be of particular relevance, since the dynamic characteristics of the vehicular environment along with the delay-critical nature of safety services turn the MAC layer timings very important. The delay model and its assumptions are outlined and applied to the slotted based approach relying in V2I communications.
- Finally, a detailed approach is outlined in order to improve safety message delivery, specifically caring about RSU's coordination for beacon transmission, as well as the careful choice of the slot used by vehicles to perform the initial broadcast of a safety event.

1.5 Document Organization

Following this Introduction, Chapter Two of this thesis makes an overview of vehicular communications, in which wireless and real-time communications are described generically, as well as the scope of vehicular networks and the relevant standards. It also details some research projects made worldwide on vehicular communications, with particular emphasis on those focused on safety.

Chapter Three presents the limitations imposed by dense scenarios on MAC techniques, as well as the real-time requirements needed to be considered. The WAVE MAC protocol is presented, as well as other general MAC protocols used in VANETs. Also, a review is made on some of the MAC techniques proposed for vehicular communications, namely those specifically based on the IEEE 802.11p/WAVE family of standards, and those related with safety message delivery. The chapter finishes with some delay performance studies, and with the substantiation of the thesis.

Chapter Four details the proposed MAC techniques, emphasizing the infrastructure based MAC protocol advantages, as well as detailing the proposals for a safety-critical and bounded delay MAC protocol within a specific scenario. An alternative solution, relying solely in V2V-based communications is also made, for cases where the infrastructure may not be accessible (e.g., tunnels), or even not feasible to have total RSU coverage.

Chapter Five refers to Validation, where a delay model is devised and analytical calculations are made in order to assess the suitability of the proposed MAC schemes.

Chapter Six contains the Conclusions and Future Work.

The Bibliography and Appendices closes the thesis.

CHAPTER 2

OVERVIEW OF VEHICULAR COMMUNICATIONS

Summary

This chapter presents an overview of wireless and real-time communications, and describes vehicular networks as well as relevant standards. It also details some research projects made worldwide on vehicular communications, with particular emphasis on those focused on safety.

2.1 Wireless Communications and Real-Time Requirements

2.1.1 Wireless Communications

Wireless communication is any type of information transference where a physical wiring between the transmitter and the receiver does not exist. The information is conveyed through the air using electromagnetic waves. Guglielmo Marconi was the first known to apply the concept of radio's communication in 1897, keeping continuous contact with ships sailing the English Channel. In the last years, and due to the development of technologies (digital and RF circuit fabrication improvements, large-scale circuit integration/miniaturization technologies, and digital switching techniques) enabling wide spread deployment, an exponential growth in the use of wireless communications was observed (RAPPAPORT, 2001). Comparing with other 20th century popular inventions (telephone, automobile, cable television), wireless communications in the consumer sector took less time to penetrate the market.

Regarding the communication flow in wireless systems, these are generally classified as: *simplex*, where communication occurs in only one direction (e.g., paging system where acknowledgments are not present); *half-duplex*, which allow two-way communication but not simultaneously (e.g., "push-to-talk" and "release-to-listen" using the same channel to transmit or receive information); and *full-duplex* radio systems, where simultaneous radio transmission and reception can occur (using separate channels – frequency division duplexing (FDD) – or adjacent time slots – time division duplexing (TDD)).

When FDD is employed, to accommodate simultaneous radio transmission channels, separate transmit and receive antennas are typically used in the based station, whereas a single antenna (with a duplexer device) is used in the mobile user unit. The channel used to convey traffic from the base station to the mobile user is called *forward channel*, while the channel used to transmit information from the mobile user to the base station is called *reverse channel*. It is usually necessary to separate transmit and receive frequencies by about 5% of the nominal RF frequency so that the duplexer can provide sufficient isolation while being inexpensive. FDD is used exclusively in analog mobile radio systems.

TDD shares a single radio channel in time, using a portion of time to transmit from the base station to the mobile and the remaining time to convey traffic from the mobile to the base station. There are not two simultaneous radio transmissions at any instant of time, but the user is given the appearance of full-duplex operation by using information bursts and storage. TDD is only possible with digital transmission formats and digital modulation. Since TDD is very sensitive to timing it should be used carefully when the physical coverage distance is high, due to the radio propagation delay.

Nowadays, wireless communication applications are far from being solely targeted to voice communication as initially. Mobile applications are spread throughout today's society, assisting us in life's everyday requirements and improving life quality. They are used, in addition to basic communication, for entertainment, location, education, healthcare and m-commerce (QUALCOMM INC., 2007). With today's mobile applications, communication is possible anytime and anywhere, being personal or interactive, such as instant/video messaging and video telephony respectively.

In what concerns the entertainment area, mobile communications give people the flexibility and freedom to be outdoors and away from home, and still enjoy and get advantage of technologic amusements. Mobile TV (live or cached), videos and movies (streaming or on demand), music, gaming, or social networking are all available.

Location-based services can be used to determine a user location anytime anywhere, finding a place when the user is lost, determining a child or elderly location, and also enabling the tracking of goods or services. Mobile access enables also enhancing the learning experience, through distance-learning, and making it possible at any instant through live or cached classes. Mobile services can also assist in health to permit freedom and mobility, and enhance quality of life, allowing outpatients monitoring and consequently faster diagnosis and timelier treatments. Finally, mobile-commerce services (m-banking and m-payment, e.g., toll payment) provide a new level of convenience for managing money transactions.

The appearance of new mobile services is closely related with advances in wireless technologies. The evolution of wireless technologies (higher data rates, optimized Quality of Service (QoS), reduced latency and increased network capacity) has enabled the progression of mobile services, which could be divided in several stages of evolution.

First, simple communication such as basic voice and text (SMS and email services) was delivered. After that, a stage focused on high-speed downloading was possible (music/video on demand, ringtones, Internet browsing and multimedia attachments to SMS and email). A third stage included high-speed uploading since the technologies achieved higher delivery efficiencies for uplink traffic transmissions, advanced QoS capabilities, improved latency reduction, and higher network capacity for more simultaneous users. Finally, the last stage of progression brings seamless fixed-mobile convergence services to enable seamless, ubiquitous connectivity between mobile networks, home networks and consumer electronics, by supporting multiple air interfaces over a common all-IP core network (e.g., transfer a video-telephony call from the mobile device to the home monitor seamlessly).

Owing to the third stage of evolution, real-time latency-sensitive mobile services allowed simultaneous voice and data services to be used, such as VoIP, PTT, video telephony and live multiplayer gaming (QUALCOMM INC., 2007). We can also think in safety-critical applications, which are usually latency-sensitive since they have time deadlines to match, in order to have the adequate performance.

2.1.2 Real-Time Requirements

Some applications have real-time requirements and demand a dependable operation. A real-time system can be defined as a system that must meet their temporal specification in all anticipated load and default scenarios (KOPETZ, 1997). This means that the correct output is dependent on the logical result but also on the time it is delivered. For instance, an anti-lock brake or air-bag system must react timely to help the driver and function properly.

Real-time system can be classified into hard or soft real-time. In the former we care very much if the system does not respond on-time, and these systems always have to react timely. Most hard real-time systems are also safety-critical, where life is at risk if timing requirements are not met (a driver could be hurt if the air-bag is not inflated in time). In soft real-time systems a timing requirement may occasionally fail to be met without jeopardizing system correctness (indicator light flashing on and off). Usually a real-time system controls some device and is composed of several sub-systems, one of which is a computer. For this reason, most real-time systems are usually called embedded systems (TINDELL, HANSSON, 1995). These are responsible for reading system inputs (e.g., sensors), perform the necessary computations and write all outputs (e.g., control actuators) in a predetermined amount of time.

Many complex computer systems are concurrent, meaning there are lots of events that could occur at the same time and must be dealt by the processor or controller, which executes concurrently and gives some computation time to each event (e.g., a driver in a car turns on the indicator light to turn, and at the “same time” brakes suddenly). The events may be asynchronous, meaning we cannot predict when they will happen (e.g., sudden brake), and also periodic or synchronous, meaning they will be repeated with a certain period for some amount of time (e.g., indicator light flashing on and off).

Timing requirements are typically expressed as a bound on the time taken to perform some computation or task, being this bound usually called a deadline. In real-time environments an entity called scheduler is responsible for ensuring that all tasks meet their deadlines. Also, it is responsible to define which entities or resources are assigned to a specific task. Priorities also come into play since it is usually to assign each task a priority, which can lead other tasks to be put on hold (preemption). Message transmission can be considered a task. At the atomic level (e.g., the start of transmission of a small part of information), this task cannot be preemted. However, at higher levels of the OSI model, where we can consider a whole message being broken down into smaller parts, preemption can occur among each smaller part. Also, for each type of message a different deadline can exist.

We could wonder if wireless technologies have a role in real-time applications. Wireless communications are known to be inherently unreliable and are often characterized by relatively high packet error rates. When hard real-time requirements are to be met despite wireless communication, it becomes even more difficult to provide safety guarantees. The central problem is that consecutive failures in message transmission may affect the correct functioning of the system, eventually jeopardizing safety in those type of applications (BARÓ [et al.], 2011). Nevertheless, wireless technologies have taken their place in industrial automation since they are easy to deploy and have the potential to save costs and support recent automation applications (e.g., building automation or sensor/actuator network for factory automation). Standards such as ZigBee and Bluetooth have been used on office and manufacturing automation.

Bluetooth standard was published in 1994 and uses radio waves in the Industrial, Scientific and Medical (ISM) band, from 2.4 to 2.485 GHz, for exchanging data between fixed and mobile devices in a master-slave configuration, which together compose a Personal Area Network (PAN). Since it is aimed at low power consumption, the communication range is short, from 1-100 meters (depending on class).

ZigBee was standardized in 2003 and is based on IEEE 802.15.4. It contains the specification for high-level communication protocols, which are used to create PANs with small and low-power devices. For most applications transmission distance is limited to 10-

75 meters in line-of-sight due to the low power consumption requirement (under the best conditions the range can be as great as 1,000 meters with a clear outdoor path, although power consumption is increased).

Although interesting and applicable to various situations, neither Bluetooth nor ZigBee can meet the stringent requirements of industrial control since these applications have stricter timing requirements when compared with office applications. For instance, a monitoring application may be expected to retrieve updates from sensors every second. Neither ZigBee nor Bluetooth original standards offer advantage over Wi-Fi in order to provide a guarantee on end-to-end wireless communication delay (EAMSOMBOON, KEERATIWINTAKORN, MITRPANT, 2008), although recent enhancements are being studied successfully in Bluetooth (DE CERIO, VALENZUELA, 2015). In addition, industrial environments are harsher for wireless applications in terms of electromagnetic interferences and obstacles than office environment. ZigBee, without built-in channel hopping technique, would surely fail in such environments, whereas Bluetooth assumes quasi-static star network, which is not scalable enough to be used in large process control systems (SONG [et al.], 2008).

Embedded systems are subject to constant and complex interactions with their physical environment via sensors and actuators. Several industrial organizations, such as ISA, HART, WINA and ZigBee, have been actively pushing the application of wireless technologies in industrial automation. Wireless sensor and actuator networks, such as WirelessHART (SONG [et al.], 2008), are setting new standards to achieve dependable designs in the domain of real-time industrial control. In several other application fields, standard technologies (e.g., IEEE 802.11) or enhancements are used and adapted to build a specific MAC layer designed to attain the required real-time properties of such application.

Vehicular networks must have inherently wireless communications supporting the exchange of information. There are particular characteristics of vehicular networks that should be taken into account when designing a suited wireless protocol. Moreover, with the major goal of safety, several vehicular applications have real-time requirements. These features along with the growth and rising interest in the field, have made several standards to be published addressing some of those specific features.

2.2 Vehicular Networks and Standards

As mentioned previously, one major driver for the use of vehicular networks is the problem of accidents and consequent injuries. This issue by itself motivates the need for some vehicular applications, which will be detailed below. Also, vehicular networks have particular characteristics which should be taken into account, namely high mobility and potentially large scale. This subsection presents some accidents statistics as well as a brief overview of drivers' behaviors, distances and timing aspects. This will be followed by some solutions and projects/standards to address the problem.

2.2.1 Accidents and Time Related Aspects

When consulting the statistics from the European Commission about accidents, fatalities and injuries along the last years (Figure 2-1), it can be seen that more than 1 million road accidents occurred every year, with at least 1.3 million injured and more than 25,000 fatalities. Vehicle enhancements in passive safety (e.g. airbags) have decreased the number of fatalities in about 25% from 1996 to 2005. However, the decrease in accidents was little more than 10%.

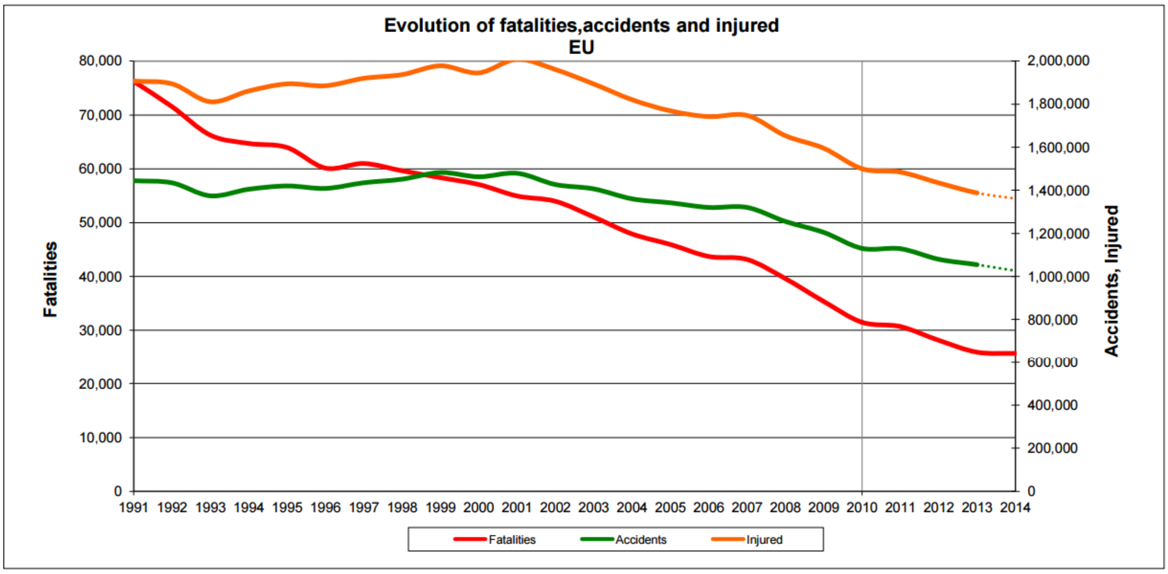

Figure 2-1. Accidents, injuries and fatalities statistics (CARE, 2015).

Whereas passive safety applications have the goal of reducing the damages and injuries caused by a crash, active safety applications aim to avoid the crash itself. In this sense, seems legitimate shifting the focus to those types of applications. This can be seen in Figure 2-2, in which crash counter measures can be viewed as a contingency counter measure for any safety warning application that may have failed to achieve its intended objective (FESTAG, 2012).

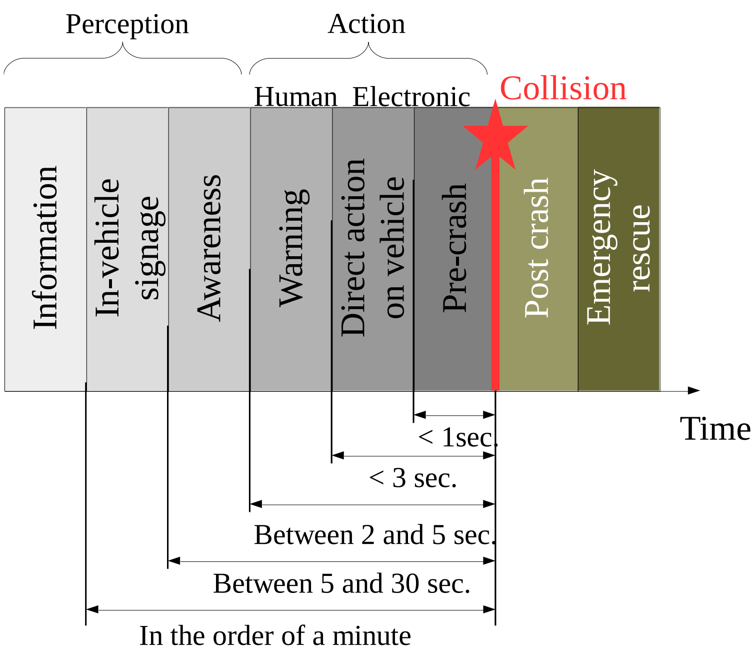

Figure 2-2. Active Safety Counter Measures Chronology before a Crash (adapted from (FESTAG, 2012)).

The transport accident statistics from European Commission indicate that in 2013, almost 26,000 persons have been killed due to road accidents (CARE, 2015). Moreover, costs of hundreds of thousands Euros are a result of those accidents. The most recent report of the WHO states that road accidents are the number one cause of deaths in the young ages of 15 to 29.

Road networks are variable and have highly dynamic scale and network density with rapid topology changes. Due to the relationship between vehicle velocity and human capabilities and limitations, speed is a primary traffic safety issue. Although inattention is the main cause for rear-end accidents, the second most common cause is following too closely (FIORANI [et al.], 2005). Different studies show that drivers do not keep safe headway distances (at least the distance correspondent to 2 seconds travelling at a certain speed). When driving in urban areas, drivers normally choose to follow a preceding vehicle within a 2 seconds region headway, which should be considered as drivers' preferred headway. Furthermore, it has been found that on motorway, the most preferred headway is around the region of 2 seconds with about 28% of drivers actually choosing a headway distance inferior to 2 seconds, and about 13% of drivers circulating with a headway distance less than 1 second. For example, if we consider vehicles moving at speeds of 115 km/h (32 m/s) and with an inter-vehicle spacing of 1 s (32 m), if for some reason the front car starts to hard-braking with deceleration of 4 m/s^2, the rear car's driver reaction time is 1.5 s, which will cause a collision (PARKER, VALAEE, 2007). If we wanted to be more accurate on driver's reaction time, several studies exist on how several factors of human behavior can influence such measure. For example, Marc Green goes a step further on driver's reaction time instead of using the standard 1.5 seconds number (GREEN, 2000). In his work, he decomposes the total reaction time in mental processing time or perception time (the time required for a driver to detect that a pedestrian is walking across the roadway directly ahead and to decide that the brakes should be applied), movement time (the time it takes to lift the foot off the accelerator pedal, move it laterally to the brake and then to depress the pedal), and finally the device response time (a driver stepping on the brake pedal does not stop the car immediately. Instead, the stopping is a function of physical forces, gravity and friction).

Table 2-1. Safety applications with greatest benefits in near and mid-term (CHEN, WEN-LONG, REGAN, 2010).

Safety application	Comm. Type	Transmit mode	Latency (msec)	Traffic Information	Communication Range (meters)
Traffic Signal Violation Warning	I2V P2M	Periodic	~100	Traffic signal status and position, timing, directionality, stopping location, road surface types	~250
Curve Speed Warning	I2V P2M	Periodic	~100	Curve location, curve speed limits, curvature	~200
Emergency Electronic Brake Lights	V2V P2M	Event driven	~100	Vehicle position, heading, speed, deceleration, road surface condition	~300
Pre-Crash Sensing	V2V P2P	Event driven	~20	Vehicle type, position, speed, acceleration, heading, yaw-rate	~50
Cooperative Forward Collision Warning	V2V P2M	Periodic	~100	Vehicle position, speed, acceleration, heading, yaw-rate	~150
Left Turn Assistant	V2I I2V P2M	Periodic	~100	Traffic signal status, timing, directionality, road shape and intersection information, vehicle position, speed, heading	~300
Lane Change Warning	V2V P2M	Periodic	~100	Vehicle position, heading, speed, acceleration, turn signal status	~150
Stop Sign Movement Assistance	V2I I2V P2M	Periodic	~100	Vehicle position, heading, speed, warning, turn signal status	~300

In an attempt to tackle some of the human limitations, several safety applications have been developed. These applications have the purpose of improving driving safety, with the final goal of reducing the number of accidents and consequently the number of injured persons. A variety of safety services have been thought of for Intelligent Transportation Systems (ITS), each service having different requirements of latency, range and type of communication. Some are applicable to highway scenarios and have hard real-time requirements (the ones concerning us the most), such as Cooperative Collision Warning, Emergency Electronic Brake Lights (EEBL), Lane Change Warning, and expanding driver awareness in potential hazardous situations as an accident or traffic ahead. In (CHEN, WEN-LONG, REGAN, 2010), Chen et al. list, based on Shulman and Deering, what they call the near and mid-term applications with the greatest potential safety benefits. Those are shown in Table 2-1. Different types (directions) of communication are used in each particular application, those being shown in the second column of the table, and may include infrastructure-to-vehicle (I2V), vehicle-to-infrastructure (V2I), vehicle-to-vehicle (V2V), which can be point-to-multipoint (P2M) or point-to-point (P2P). Each application can be event-driven or periodic in its nature (this is shown in the third column). The type of information being exchanged in each application, as well as the typical relevant range are shown in columns five and six respectively. Of particular interest is the fourth column of Table 2-1 which refers to latency. It is important to note the difference between medium access control (MAC) layer end-to-end delay, and what we can call the total application layer end-to-end delay. In the definition and classification of performance metrics made in (BAI, 2006), they divide between network-level (or packet-level) and application-level metrics. These are both important in what concerns analyzing protocol behavior under different environments and user dynamics, as well as being a key issue to have in mind when developing a protocol. Examples of the first include: packet delivery ratio (PDR) and average per-packet latency (AP-PL). An example of the latter is QoS performance requirements of voice over IP (VoIP) and video streaming applications (end-to-end latency of about 50-100 msec). The mapping between packet-level metrics and application-level metrics is generally non-trivial. Examples of some metrics can be seen in Figure 2-3.

The relation between network-level and application-level metrics for the various application sub-classes is also discussed in (BAI, 2006). Regarding broadcast(geocast)-based safety applications, the PDR (probability of successfully receiving packets at distance *d* from broadcasting vehicle) and AP-PL (duration between the time of generating a packet at sender vehicle and the time of successfully receiving it at receiver vehicle, where only successfully received packets are counted) are the two major network-level metrics and allow protocol designers responding several questions, namely “What is the maximum backoff time experienced by the MAC for a given network density?”. However, these metrics are of limited utility from an application perspective, because performance requirements are typically given in terms of application-level metrics as opposed to packet-level metrics.

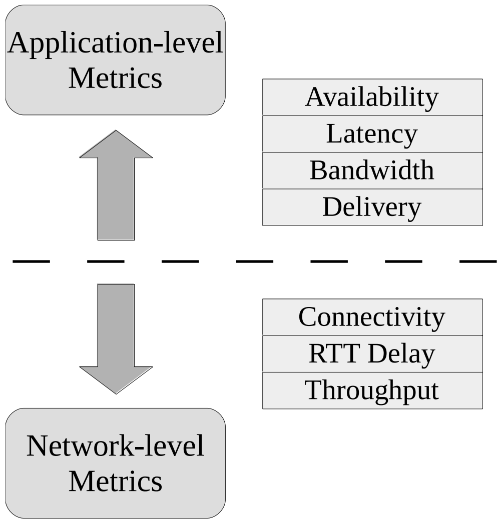

Figure 2-3. Different level metrics.

2.2.2 Characteristics and Applications

The today's society is organized in such a way that vehicles ubiquity along with the exponential growth of technologic means, namely the new wireless communication systems, led to the development of an intelligent transportation systems (ITS) infrastructure, and considerable interest from the automotive industry as well as the research community. This infrastructure should support a variety of new services/applications related with infotainment (e.g., Internet access from vehicles) but also those related with the enhancement of public safety (e.g., collision avoidance) and traffic efficiency. So, vehicular communication networks (VCNs) rely in wireless communications to provide distinct services to mobile users (vehicles).

Depending on the entities involved in the communication, as well as the involving scenario (rural, city, or highway environment) we can have different architectures deployed in such networks. In vehicle to vehicle (V2V) systems the information is exchanged usually only between vehicles, with no infrastructure support in a purely ad-hoc network. In vehicle to infrastructure (V2I) systems data exchange relies on fixed units on the road-side (RSUs) that are usually connected via a wired backbone. These RSUs can be property of private network operators / service provider companies or the government. We can also think of a hybrid architecture, where the infrastructure is present only at certain road segments to improve performance and service access. The vehicles are able to communicate due to a device usually called on-board unit (OBU). This device is also connected (wired or wirelessly) with other units in the vehicle, such as sensors or actuators. Hereafter the term

OBU, vehicle or car is used interchangeably. We can get an adequate overview of the whole system by looking at the reference architecture proposed within the Car-to-Car Communication Consortium (C2C-CC) (C2C, 2007) (Figure 2-4), where AU stands for Application Unit.

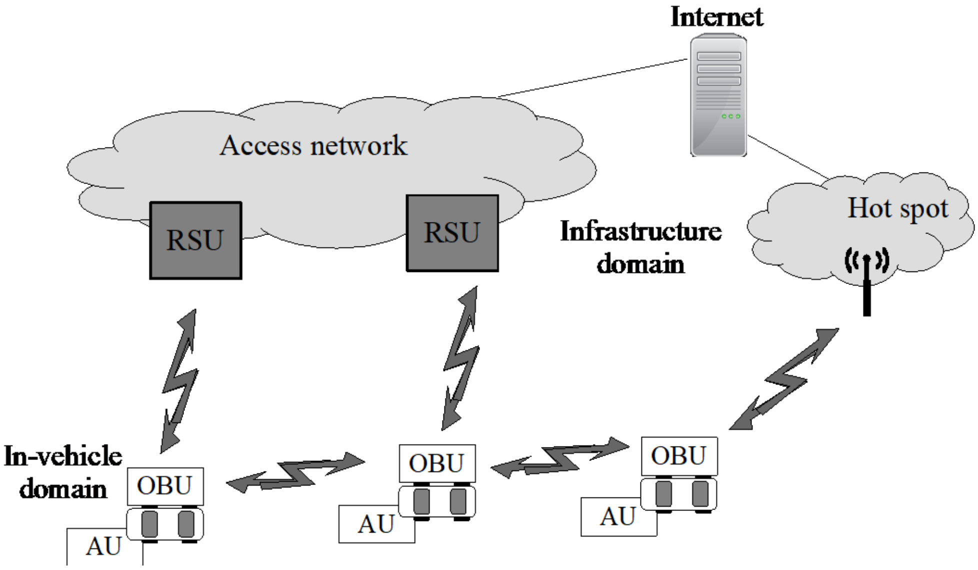

Figure 2-4. C2C-CC reference architecture (adapted from (C2C, 2007)).

In the scope of this work, the RSU takes a central role within the network. Thus, it is interesting to detail two main functions, related with safety, and procedures associated with the RSU, according to (C2C, 2007). Firstly, the RSU can extend the communication range of a vehicle by re-distributing the information to other OBUs and, by being coordinated with other RSUs, forward it to other OBUs (Figure 2-5). Secondly, running different safety applications and by using I2V communication acting as an information source (Figure 2-6).

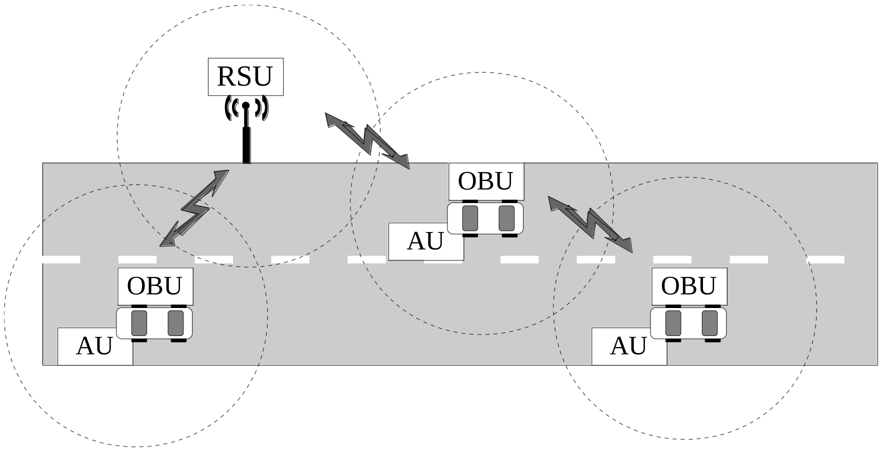

Figure 2-5. RSU extending the range of an OBU by forwarding data to other OBUs (adapted from (C2C, 2007)).

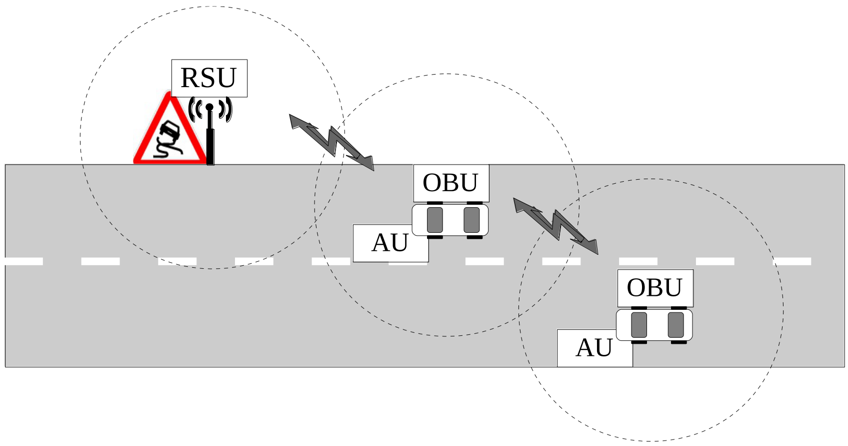

Figure 2-6. RSU work as information source running safety applications (adapted from (C2C, 2007)).

Vehicular networks present unique characteristics from which advantage should be taken, namely (PIERRE, 2010):

- Energy abundance, since nodes (within vehicles) can provide continuous power to computing and communication devices;
- High computational capability, since operating vehicles can afford significant computing, communication, and sensing capabilities;

- Predictable mobility, since vehicles movements are usually confined to roadways and therefore predictable. With positioning systems (e.g., GPS), current speed and road trajectory, the future position of a vehicle can be predicted.

However, attention should be paid to the various challenges faced in those networks:

- Potentially large scale. Most ad hoc networks assume a limited area, but in VCNs that area may extend over the entire road and also include many participants;
- High mobility. The vehicular networks environment is extremely dynamic and with extreme configurations, since in highways relative speeds of up to 300 km/h may occur, while in suburban low busy roads the density of vehicles may be 1-2 per kilometer; It should be noted however that suburban highways exist, where traffic density is usually high, and vehicles can have considerable high velocities sometimes, or be stopped at other times, which poses also serious challenges; however, this work is confined to highways.
- Different communications environments. The communication environment of a highway is relatively simple (e.g., constrained one-dimensional movement) and is substantially different of that experienced inside a city, since buildings, trees and other obstacles are frequent and make communication much more complex (direct line of communications may be rare).
- Frequently disconnected network when considering V2V. For the same reason of the previous, in low vehicle density scenarios the network may be disconnected with higher probability, which may be a problem in some applications (e.g., ubiquitous Internet access). In a full infrastructure covered road this problem would be solved.
- Security. This is a crucial aspect to make VCNs reliable and accepted by the customers, and to bring safety on public roads. This includes authenticity, message integrity and source authentication, privacy, and robustness.
- Quality of service. Applications for vehicular networks require fast association and low communication latency to guarantee service's reliability for safety-related applications (which are time sensitive), and quality and continuity of service for infotainment-oriented applications.
- Market technology penetration. If we do not rely on a fixed infrastructure, the value of V2V communication is only recognizable in case a sufficient penetration rate of equipped vehicles has been reached. This means car manufacturers have to gradually

> endow vehicles with wireless technologies and provide attractive infrastructure based services (e.g., car-to-home data exchange or location based services) to motivate drivers to invest in such equipment. Only then, and when high penetration rates can be reached, it will be possible to allow for purely ad-hoc vehicular communication services such as intersection collision warning, local danger warning, and a decentralized dissemination of real-time traffic flow information.

There are different application areas/scenarios where vehicular networks can be used. Although the vehicular network communication may be centered on the primary concern of safety-related services to reduce the number of accidents in our roads, the OBUs may use infotainment services by connecting to the Internet via RSUs or Wi-Fi spots. In the absence of these, if the OBU has integrated cellular radio networks (GSM, GPRS, UMTS, WiMax and/or 4G) communication capabilities, it can also connect to the Internet. As seen in (PIERRE, 2010), "*The integration with on-board sensor systems, and the progressive diffusion of on-board localization systems (GPS) make VCNs suitable for development of active safety applications, including collision and warning systems, driver assistance and intelligent traffic management systems. On the other hand, inter-vehicular communication also fuels the vast opportunities in online vehicle entertainment (such as gaming or file sharing), and enables the integration with Internet services and applications*".

2.2.3 Vehicular Communication Standards

Research related to inter-vehicular communications starts in the early 1980s by JSK (Association of Electronic Technology for Automobile Traffic and Driving) of Japan, whose work was focused on group cooperative driving. In terms of standards, major standardization organizations and governmental authorities had the perception of vehicular networks' importance and therefore have taken measures to allow practical implementation of those networks. DSRC system has emerged in North America, where 75 MHz of spectrum at 5.850-5.925 GHz frequency band was approved by the U.S. Federal Communication Commission (FCC) in 2003, in order to support communication especially in vehicular networks. The C2C-CC was initiated in Europe by vehicle manufacturers and automotive equipment manufacturers, as well as research community, with the main objective of increasing road traffic safety and efficiency by means of inter-vehicle communication (AUERBACH, 2008).

The ISO TC204 Work Group 16 defined a basic set of standards. The nowadays called Communication Access for Land Mobile (CALM) defines a set of wireless communication protocols and air interfaces for a variety of applications and communication scenarios to be used within ITS. Several communication modes are allowed (V2I, V2V and I2I) and a set of protocol standards allow to route data over the most wireless technology (Infrared, GSM, DSRC, WAVE, WiMAX, Bluetooth, RFID and others), based upon knowledge of the QoS requirements for that application and real-time performance of the available communications media.

The WAVE standard (sometimes named DSRC 5.9 GHz) aims to integrate safety and non-safety services in V2V and V2I communications. These standards should provide very low latency to support safety real-time applications, operating at speeds up to 200 km/h and ranges up to 1,000 meters, and, at the same time, non-safety applications providing data rates up to 27 Mbps. WAVE is an amendment to the well-known IEEE 802.11 standard to support V2I and V2V communications with highly mobile nodes. It operates near the 5.9 GHz band in North America and Europe and comprises several standards. The first version of some was published in 2006 with successive updates published until 2014. WAVE includes IEEE 802.11p, which entails the MAC (using 802.11e QoS amendment) and PHY (using 802.11a amendment) layers, and the main difference relatively to legacy 802.11 is the absence of Access-Point (AP) functionality and time-consuming authentication/association procedures. It also defines how applications will function in its specific environment, based on the management activities defined in IEEE P1609.1, the security protocols defined in IEEE P1609.2, and the network layer protocol defined in IEEE P1609.3. A comparison between the WAVE protocol stack and the TCP/IP protocol stack can be seen in Figure 2-7.

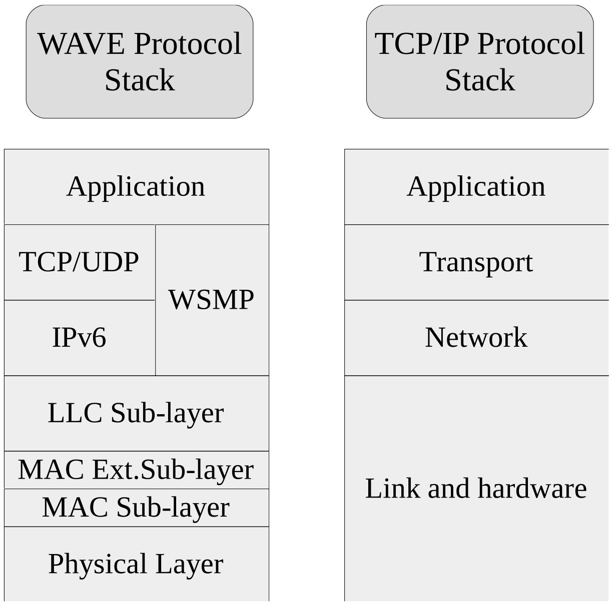

Figure 2-7. Comparison between WAVE protocol stack (left) and TCP/IP protocol stack (right).

The WAVE standard uses a multi-channel concept which can be used for both safety-related and mere infotainment messages. The spectrum is structured in the upper 5 GHz range and relies into seven 10 MHz bandwidth channels (EICHLER, 2007). The band is free but licensed (presents usage and technology restrictions). It uses one control channel (CCH) – CH 178 – reserved for safety relevant applications and system control and management with high priorities. The messages related with those applications are broadcasted and usually short in length. Four channels (174, 176, 180 and 182) are used as service channels (SCHs), mainly supporting the non-safety relevant applications. There are two safety-dedicated channels (172 and 184), the first one providing security solutions while the second playing a protective role against congestion on other channels. Figure 2-8 shows the channels' spectrum distribution using 10 MHz channel spacing.

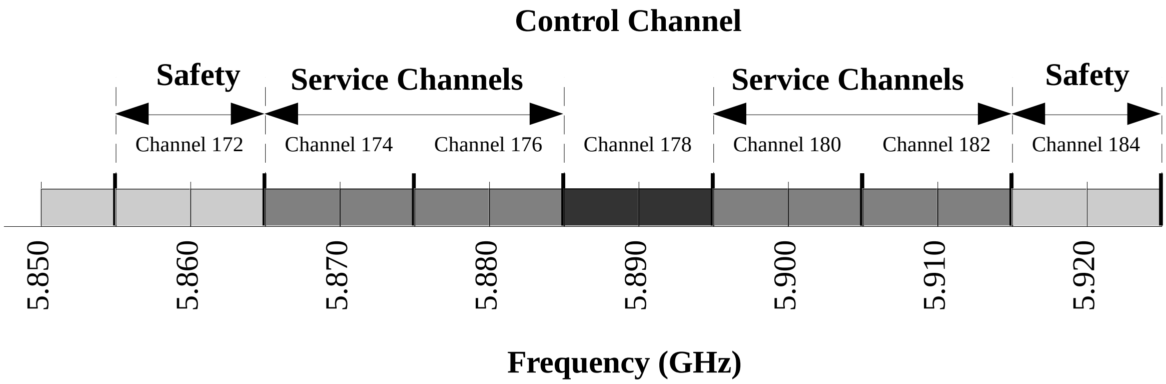

Figure 2-8. 75 MHz DSRC Spectrum.

Since the communication time interval of WAVE stations (STAs) is very limited, the overhead needs to be as low as possible. Thus, a WAVE Basic Service Set (WBSS) does not require MAC authentication and association prior to being allowed to transmit data. In a WBSS, a WBSS user only needs to receive the WBSS service announcement frame (WSA) from a WBSS provider before starting transmissions. Contrarily to ordinary IEEE 802.11, beacon frames are not used. Therefore, to achieve synchronization an external time reference like GPS has to be used.

Safety messages are event-driven and broadcasted over the CCH. However, periodic data can also be transmitted over the CCH, namely short status messages, also called WAVE Short Messages (WSMs), and WBSS establishment and advertisement messages (WSAs). Beacons have status information about the vehicle position, its speed and direction, thus being useful to cooperative applications, such as collision avoidance and driver assistance. Since beacons require accurate and timely information from the network, their generation rates are in the range 5-10 Hz (meaning one in every CCH interval or one in every two consecutive CCH intervals). WSAs are sent to advertise a WBSS set-up (and the related parameters) that provides connectivity and transport of non-safety services during the SCH interval (JIANG, DELGROSSI, 2008).

For single radio devices, the channels cannot be used simultaneously. Therefore the coordination of channel access has to be done efficiently. A global synchronized channel coordination scheme is defined in IEEE 1609.4 (IEEE WAVE, 2010), which also describes enhancements to 802.11 MAC layer in order to support WAVE. The channel time is divided into synchronization intervals with a fixed length of 100 ms, consisting of a CCH interval and a SCH interval. For safety-critical focus, all devices should tune to CCH during all CCH intervals, where high priority frames are transmitted. During SCH intervals, devices can optionally switch to SCHs, which are used for non-safety applications (YUNPENG ZANG [et al.], 2007). When the entity is a multi-physical layers device, each physical layer continuously monitors either CCH or SCH. For a single physical layer device, there are different types of access schemes dependent on whether the device accesses a specific channel in its corresponding time interval. This is shown in Figure 2-9. Alternating access was initially thought as the standard access method, and means the device is tuned on the CCH during the CCH synchronization interval, and tuned on the SCH during the SCH synchronization interval. When using continuous access the device remains continuously tuned on the same channel (CCH or SCH). Immediate access is used when a device needs to immediately tune another channel during the synchronization interval of the other channel (CCH to SCH or vice-versa), and tuning again to the channel that was left in the following correspondent synchronization interval. Finally, extended access means the device immediately tunes another channel during the synchronization interval of the other channel and remains there even in the following synchronization intervals of the channel that was left.

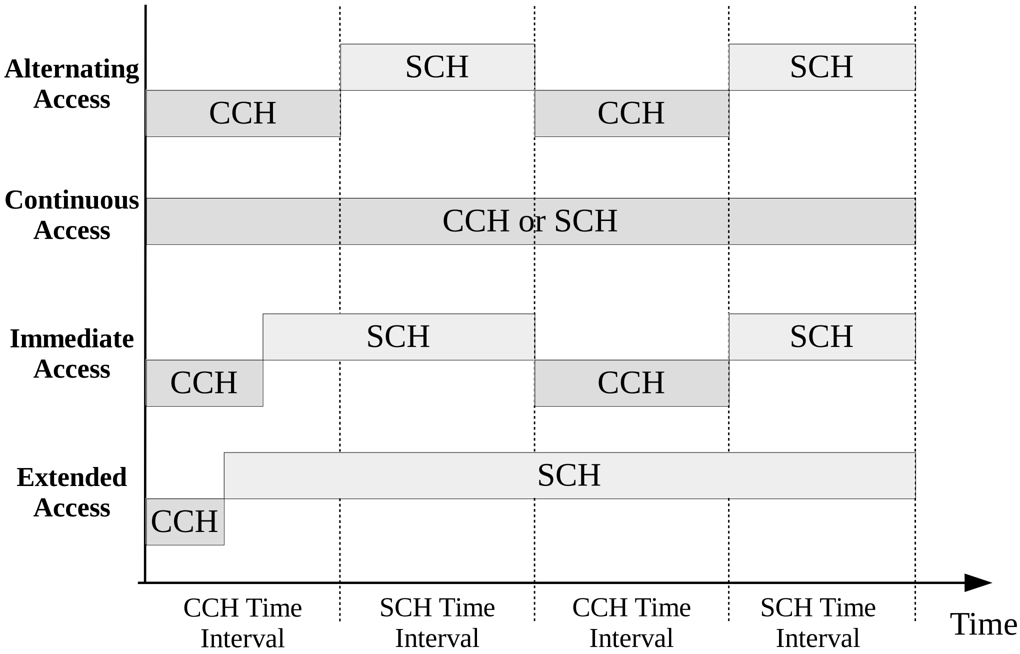

Figure 2-9. WAVE multi-channel operation (different types of access)

Another popular standard, particularly in Europe, is the ETSI ITS-G5. Its global operating mode is similar to WAVE. ETSI covers 30 MHz (5.875 to 5.905 GHz) dedicated to ITS for safety applications, and uses 10 MHz channel spacing, with one CCH, G5CC, and four SCHs (G5SC1 and G5SC2 also used for safety applications). Although in WAVE is optional and accounted for, ITS-G5 uses continuous CCH operation. It is required that every station operating on both G5CC and one of the G5SCs have to be able to receive data on both channels simultaneously. Cooperative Awareness Messages (CAMs) are typically broadcasted as periodic beacons with frequency of 1-10 Hz. One particular feature in ITS-G5 regarding medium utilization is Decentralized Congestion Control (DCC). It aims at overcoming the difficulty present in 802.11 CSMA/CA plus EDCA of dealing with high network loads. DCC is mandatory for all stations in order to maintain network stability, throughput efficiency and fair resource allocation. This feature shapes ad-hoc network traffic in order to ensure proper operation of safety applications, by reducing high channel loads that can lead to longer channel access delays and increased packet collisions. The channel overload is avoided essentially by measuring locally the channel busy ratio and controlling message rate (if a threshold is exceeded). However, DCC requires mechanisms on all layers of the protocol stack and harmonization between those among the layers. In (CHEN, CHENNIKARA-VARGHESE, CAI, 2005), the authors state that the DCC algorithm simultaneously regulates no less than four parameters that all work for identical purposes. This could be excessive, leading DCC to perform sub-optimally. The authors showed in their work that a physical layer data rate control, which is only one of the four parameters used, achieves a better result.

2.2.4 Vehicular Communication Projects

With the introduction and promised potentialities of wireless technologies supporting safety applications, several international projects supported by automobile manufacturers, private companies and research institutes, were developed worldwide. They shared a common goal of creating a communication platform for inter-vehicle communication.

Next, some finished and current projects are listed and shortly described. They are divided into two categories, one where safety information is exchanged and taken into account, and the other where different vehicular communication issues, other than safety information, are addressed. Figure 2-10 places all the described projects in a time line. The ones on the top are those where safety-critical information is specifically addressed, the ones on the bottom those where safety information is not taken into account, and the ones in the middle those where general safety information is taken into account (be it safety-critical or not).

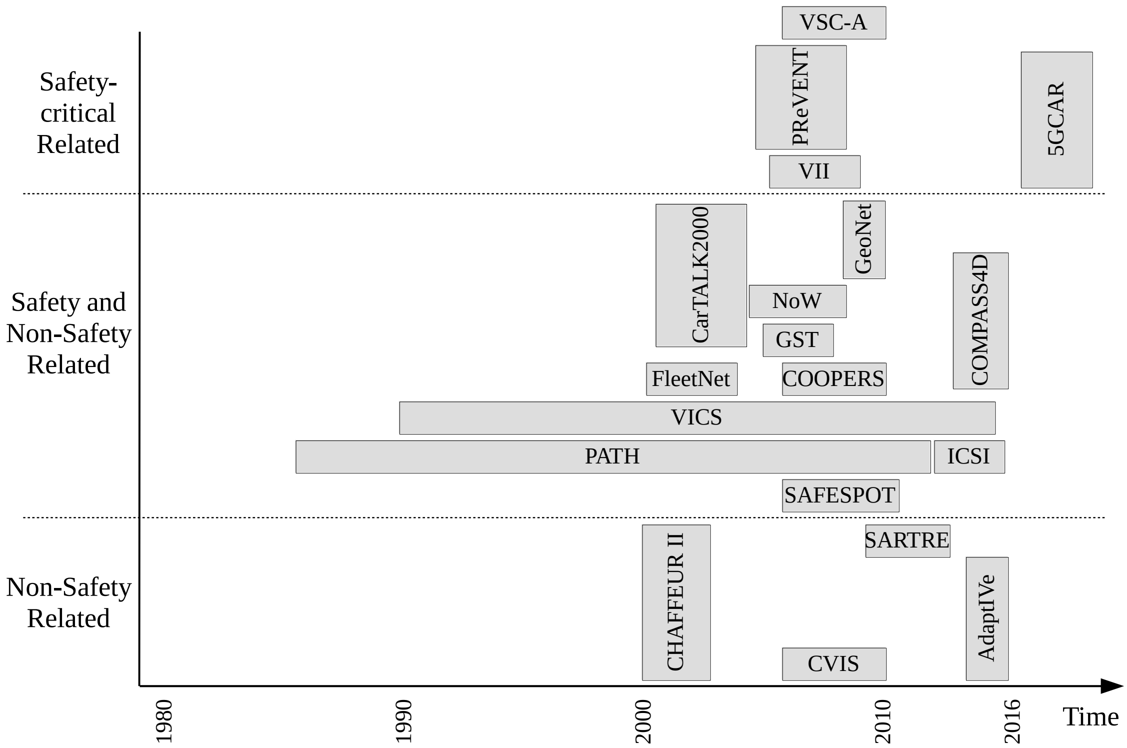

Figure 2-10. Worldwide projects related with vehicular communications

2.2.4.1 Projects including safety-critical information exchange

FleetNet - Internet on the Road, was a project in Germany that produced results in terms of experimental characterization of VANETs, novel network protocols proposal (MAC, routing) and exploration of different wireless technologies. Its main applications' areas were cooperative driver assistance (e.g., obstacle warning), decentralized floating car data (e.g., traffic jam monitor), and user communications and information services (e.g., Internet access). (September 2000 - December 2003)

CarTALK2000, an IST European project, was focused on new driver assistance systems which are based upon inter-vehicle communication, and had as main objectives developing co-operative driver assistance systems and developing a self-organizing ad-hoc radio network to serve as communication basis for a future standard. (August 2001 - August 2004)

NoW (Network-on-Wheels) is a project joining the efforts of German industry and academia to solve technical questions on communication protocols and data security for V2V communications, and contribute to standardization efforts of C2C-CC. It is successor of the project FleetNet, focused on communication aspects for V2V and V2I based on WLAN technology. The specific objective is integrating both safety and non-safety applications in a reliable communication system. (May 2004 - May 2008)

SAFESPOT (Cooperative vehicles and road infrastructure for road safety) is an integrated research project co-funded by the European Commission Information Society Technologies. "The cooperative approach envisages a scenario in which the vehicles and the infrastructure cooperate to perceive potential dangerous situations extended in space and time horizon that will only be limited by the range of the radio communications", in SAFESPOT vision. A "safety margin assistant" will be developed to detect in advance dangerous situations and extend the driver's awareness of the surrounding environment. V2V and V2I communication is used based on WLAN technology (IEEE 802.11p). (February 2006 - February 2010)

VSC-A (Vehicle Safety Communications - Applications), a project funded by the U.S. government through National Highway Traffic Safety Administration and U.S. Department of Transportation, aimed to develop and test communication-based V2V safety systems to determine if DSRC at 5,9 GHz, in combination with vehicle positioning, could improve upon autonomous vehicle-based safety systems and/or enable new communications-based safety applications. (December 2006 - December 2009)

COOPERS (Co-operative Systems for Intelligent Road Safety) is another project to increase overall road safety and enable co-operative traffic management (developing innovative telematics applications on the road infrastructure) via continuous wireless communication between vehicles and road infrastructure on motorways. It attempts to improve road sensor infrastructure and traffic control applications able to cope with the requirements for I2V communication, and demonstrates results at major European motorways with high-density traffic. (February 2006 - August 2010)

PReVENT (PReVENTive and Active Safety Applications) aimed at developing, testing and evaluating safety related applications, using advanced sensor and communication devices integrated into on-board systems for driver assistance. (February 2004 - January 2008)

GST (Global Systems for Telematics) was an EU-funded Integrated Project that aimed to create an open and standardized end-to-end architecture for automotive innovative telematics services. It strove to deliver such infrastructure-oriented services cost effectively. With GST, drivers would be able to rely on their on-board integrated telematics system to access a dynamic offer of on-line safety, efficiency and comfort enhancing services wherever they drive in Europe. (March 2004 - March 2007)

The VII (Vehicle Infrastructure Integration) Initiative in North America was a cooperative effort between Federal and State departments of transportation (DOT’s) and automobile manufacturers. The aim was to deploy an enabling communications infrastructure that supported V2I as well as V2V communications, for a variety of vehicle safety applications and transportation operations on major U.S. roadways. It was supported by a radio spectrum at 5.9 GHz, specifically allocated for DSRC. (2005 - 2009)

GeoNet project resulted on ETSI publication of contributed GeoNetworking protocol standard and IPv6-over-GeoNetworking adaption layer standard (ETSI, 2011), which lead several companies and institutes to implement these standards worldwide. GeoNet implemented the networking mechanism for reliable and scalable delivery of position information to all relevant vehicles. It implemented a reference system for vehicular ad hoc networking using concepts for geographical addressing and routing. The protocol was used to deliver safety messages between cars but also between cars and the roadside infrastructure within a designated destination area. (February 2008 - February 2010)

The Vehicle Information and Communication System (VICS) in Japan aims to deliver real-time road traffic information to road vehicle drivers on a car-navigation system. It can be transmitted using different technologies such as IR, microwaves in the ISM and FM. The information can be shown as text, graphics or map display. It has been shown a significant effect on reduction of congestion, decrease in the number of accidents as well as environment friendly factors, such as reduced petroleum consumption and carbon dioxide emission. (1990 - Present)

California Partners for Advanced Transit and Highways (PATH), was the first research program in North America focused on the subject now known as ITS. Initially the program was mainly focused in deploying automated platooning systems through the transmission of data among vehicles, for congestion control, but its growth until recently led to a variety of other research related areas (traffic operations, transit operations, transportation safety and policy and behavior). (1986 - 2012)

ICSI (Intelligent Cooperative Sensing for Improved traffic efficiency), funded by the EU, aimed to define a new architecture to enable cooperative sensing in ITS, and to develop a reference end-to-end implementation. The system, with a fully distributed architecture, aimed at achieving significant management efficiency in parallel with increased safety, by means of a semi-automatic accident detection and recovery system involving the main stakeholders. (November 2012 - April 2015)

COMPASS4D, a project funded by the European Commission, deploys three services: red light violation warning, road hazard warning and energy efficient intersection. This is done in seven European cities in order to prove the concrete benefits of cooperative systems for citizens, city administrations and companies. It uses different communication technologies such as ETSI ITS-G5 and 3G/LTE (Long Term Evolution). (2013 - Present)

5GCAR, is a recent project that aims specifically at researching the tools, protocols, and techniques to support Vehicle-to-Everything (V2X) connectivity, based on 5G networks. It is intended to develop an overall 5G system architecture providing optimized end-to-end V2X network connectivity for highly reliable and low-latency V2X services, which supports security and privacy, manages quality-of-service and provides traffic flow management in a multi-link V2X communication system. The project has research activities in all the stack layers and aims to demonstrate and validate the developed concepts and evaluate the quantitative benefits of 5G V2X solutions using automated driving scenarios in test sites. (2017- Present)

2.2.4.2 Projects without safety-critical information addressed

CVIS (Cooperative Vehicle Infrastructure Systems) is a major European research and development project aiming to design, develop and test a wide range of wireless technologies (GPRS and UMTS, WLAN, DSRC and IR) needed to allow V2V and V2I communications. The aim was to begin a revolution in mobility for travelers and goods. Since full interoperability between vehicles and infrastructure is needed, a mobile router was developed using a wide range of communication media. Access to these technologies is based on CALM standard that allows vehicular networking implementation to be integrated to the CVIS platform via standardized CALM service access points. (July 2006 - June 2010)

AdaptIVe (Automated Driving Applications & Technologies for Intelligent Vehicles), has the goal to develop and test new functionalities for cars and trucks offering partially automated and highly automated driving. Necessary cooperative interaction between the driver and automated systems shall be enabled by advanced sensors, cooperative vehicle technologies and adaptive strategies. This project is integrated in the C2C-CC. (January 2014 - Present)

CHAUFFEUR II built on the CHAUFFEUR I Tow-Bar function. It has widen the applications by offering truck platooning capabilities and effective driver assistant functions. Platooning strategies were transferred to the demonstration vehicles and concepts for platoon driving were developed. The communication concept for platoon vehicle-vehicle communication was developed together with a safety concept for platoon operations. A three-truck platoon was realized and demonstrated in test track environments. It should be noted that although platooning can be considered safety-critical (in the sense that will allow many cars or trucks to accelerate or brake simultaneously), it is not considered here as so, but as a technologic traffic strategy to increase the capacity of roads. (January 2000 - May 2003)

SAfe Road TRains for the Environment (SARTRE), funded by the European Commission, aimed to develop strategies and technologies to allow vehicle platoons to operate on normal public highways with significant environmental, safety and comfort benefits. Also, HAVEit

(February 2008 - June 2011) and CityMobil (May 2006 - December 2011) were similar European projects in cooperative vehicle-highway automation. (September 2009 - September 2012)

Due to the wide number of projects developed worldwide until now, with the main focus being on the fundamental issues related with vehicular communication, a solid knowledge foundation was offered to the scientific community. It seems now that there is a shift towards other related aspects:

- Projects that aim to attach public awareness to the perspectives opened by ITS technologies and applications in making vehicles smarter and safer;
- Ecological concerns in what can be called green driving (e.g., project SAGE - Safe and Green Road Vehicles Europe - aims to make road vehicles radically more green, safe and intelligent using research and technical solutions);
- Enhancing security issues (e.g., project PRESERVE – Preparing Secure Vehicle-to-X Communication Systems - wants to bring secure and privacy-protected V2X communication closer to reality by providing and field testing a security and privacy subsystem for V2X systems).

The safety-oriented projects developed for vehicular networks usually rely on the use of a vehicular communication standard. These standards typically deal with the real-time requirements imposed by those networks. One of the crucial elements needed to satisfy the requirements is the MAC layer. Several aspects need to be taken into account, and these will be subject of study in the following chapter.

CHAPTER 3

MAC TECHNIQUES IN VEHICULAR COMMUNICATIONS

Summary

This chapter presents the limitations imposed by dense scenarios on MAC techniques, as well as the real-time requirements needed to be considered for safety critical vehicular applications. The WAVE MAC protocol is presented, as well as other general MAC protocols used in VANETs. Also, a review is made on some of the MAC techniques proposed for vehicular communications, namely those specifically based on the IEEE 802.11p/WAVE family of standards, and those related with safety message delivery. The chapter finishes with some delay performance studies, and with the substantiation of the thesis.

The challenges faced in a vehicular network in terms of safety-message timely delivery are mainly addressed in the MAC layer. As already said, this is done through transmissions scheduling and medium reservation functions. This chapter begins with an introduction to the limitations imposed by dense scenarios in vehicular networks, as well as the requirements for MAC protocols to adequately deliver time-critical safety messages. Following this, the standardized WAVE MAC protocol is described, as well as other general MAC protocols used in VANETs. It is intended to explain the operation principles as well as their advantages and disadvantages regarding some important characteristics in a wireless medium. Some MAC layer schemes specifically targeted for safety message delivery are also reviewed, as well as some studies done on the delay performance of IEEE 802.11 based protocols. To finish the chapter, the substantiation for the thesis is detailed.

3.1 Dense Scenario Limitations and MAC Requirements for Safety Message Timely Delivery

The recent standards may take into account several aspects such as mobility of vehicular networks, high vehicle's speed, and synchronization to an absolute external time reference. However, even with implementations conforming standards, there are open issues/challenges regarding safety-critical applications, namely the timeliness of message transmission. Thus, it is possible to highlight two key points in such applications:

- Low channel access delay with a well-defined upper bound is typically required;
- An overload situation is possible and likely to occur in a vehicular network where the number of vehicles exceeds largely the resources available. In this situation, a "new" vehicle needing medium resources to transmit a safety-critical message should be able to access the medium within a bounded time.

When dealing with road traffic, a dense automotive scenario is most common in urban or even suburban highway areas. This relates to the absolute number of vehicles in the road. In such context, that scenario is less common in highways. However, we can get a so-called dense scenario in which the meaning of "dense" is not directly related with the absolute number of vehicles. So, taking as context the delivery of safety messages within an appropriate time bound, "dense" refers to a situation where the available bandwidth/medium for scheduling a new safety message transmission is almost or even fully filled. Therefore, the MAC layer protocol plays a major role in scheduling safety messages transmissions in order to deliver them timely. Typically, the MAC protocol is designed to suite a specific network topology and communication model.

Even in an environment where time-bounded deliveries are not a major concern, e.g., some Mobile Ad Hoc Networks (MANETs), efficient MAC protocols are needed to avoid transmission collisions and provide the QoS required by the application layer. Only few of these protocols can also be applied to VANETs due to their particular characteristics:

- Nodes are vehicles with high mobility and speed.
- Frequent and fast topology changes are experienced as a consequence of the mobility and speed;

Due to their specific characteristics, efficient medium sharing is difficult to be performed in VANETs. Although it tends to be hard to accomplish, there are some positive points:

- Vehicles are usually moving only on predetermined roads;
- Nodes do not have the problems of resource limitations in terms of data storage and power.
- GPS can provide vehicles' geographic position and time synchronization through the network. Standard GPS receivers with augmentation systems can provide an accuracy of about 3-5 meters. If better accuracy is required, such as in Advanced Driver Assistance applications, other options are available. For instance, in (HOUDALI [et al.], 2014), it is presented a system that allows estimation of the vehicle lateral position in real-time, by ensuring cooperation between an on-board vehicle system (with a sensor) and passive transponders integrated in the lateral white strips of the road. Based on an optimization method, the lateral position vehicle is provided with a distance error less than 3 cm.

Typical applications to be used in these networks are the ones called Active Safety applications, which are designed to prevent accidents and therefore need high reliability and minimal transmission collisions. Briefly, we can state that in Active Safety applications, in general, the amount of information to be transmitted is small but it needs to be done with high reliability and small delay.

The design of a MAC protocol for emergency message dissemination in a typical VANET (ad hoc network topology) is challenging for several reasons. Until nowadays, most commercially wireless networks were designed for being used in a centralized topology/control and unicast-based communication, with feedback allowable due to the point-to-point connection between nodes. In the opposite, when dealing with VANETs, the nodes are always mobile and broadcast based communication is used in a decentralized network topology. The MAC protocol thus needs to be:

- Fully distributed and self-organizing, since there is no base station that coordinates scheduling in a centralized fashion, and because vehicles' movement leads to constant changes of nodes.
- Scalable: since there is no centralized control, scalability is a very important issue to also address, in the sense that the number of vehicles cannot be restricted. This means the MAC protocol should not be blocking in the sense that it can cope with overloaded situations.

As stated in (ETSI, 2012), the data traffic models found in VANETs are different from, for example, Wi-Fi or 3G. The predominant traffic type for newly born safety applications is periodic messages (short status message with the position and speed of a vehicle), with an update rate of 1 Hz to 10 Hz, which will coexist with event-triggered hazard warnings when road traffic safety networks reach full penetration. Therefore, the communication model has some important features:

- It is mainly time-triggered with broadcasts (contrarily to the predominant event-driven model of the centralized commercial networks in existence till today);
- Transient high network loads must be supported due to the repetition (rebroadcast) of safety messages to increase reliability. This is due to the fact that using broadcasts impairs the use of techniques such as ARQ (acknowledgment of all packets);
- Unpredictable delays (on channel access or transmission collisions) should not exist since they could be intolerable because of the real-time deadlines emergency messages have;
- Packets leading to high overload can deteriorate the fast data exchange required, by limiting the available bandwidth.

In the following sections several MAC protocols are briefly explained, and their analysis is done taking into account the needed requirements. Table 3-1 summarizes the pros and cons of the most important protocols for vehicular communication networks (VCNs).

Table 3-1. MAC protocols for VCNs – advantages and disadvantages.

PROTOCOL	Comm. Type	Advantages	Disadvantages
STDMA (LANS, 1996)	V2V	+ Scalable + Upper bounded delay	- Unintentional slot reuse - Position messages needed (for scalability) - Requires time synchronization
ADHOC (BORGONOVO [et al.], 2004)	V2V	+ Relatively good QoS + No hidden node problem + Small number of relaying nodes (vs. Flooding)	- Not scalable - Requires time synchronization
V2V Safety Messaging in DSRC (QING XU [et. al], 2004)	V2V	+ High probability delivery + Safety message repetition	- CSMA/CA based - Random slots chosen
CSMA/CA (IEEE 802.11, 2007)	V2V (V2I)	+ Minor coordination + Low overhead	- Unbounded delay - Not scalable (- Hidden node problem)
MS-Aloha (SCOPIGNO, COZZETTI, 2009)	V2V	+ Scalable + Upper bounded delay	- Increased overhead (information of all slots) - Requires time synchronization
WAVE 802.11p (IEEE 802.11p, 2010)	V2I V2V	+ Prioritized channel access + Low overhead	- CSMA/CA based - “Statistical” priority
RAMC (LIU [et al.], 2011)	V2V I2V	+ Safety and non-safety delivery ratio assured + Service channel users have CCH awareness	- Not specified how the safety event is detected - Requires time synchronization
CAH-MAC (BHARATI, ZHUANG, 2013)	V2V	+ Cooperative + Increased reliability (probability successful transmission)	- Not scalable - Large overhead - Requires time synchronization
VeMAC (OMAR, ZHUANG, LI 2013)	V2I I2V	+ No hidden node problem + Reliable broadcast (implicit acknowledge)	- Overhead (large control information on CCH) - Density of vehicles not considered in either direction
Token Passing (BALADOR [et al.], 2015)	V2V	+ No synchronization needed + Reliability (vs. 802.11p)	- Separate service channel (additional transceiver) - Token recovery mechanisms
V-FTT (MEIRELES, FONSECA, FERREIRA, 2015)	V2I	+ Real-time guarantees + Redundant scheduling	- OBU registration needed - Requires time synchronization
POCA-MCVN (CHU, FENG, LIN, 2015)	V2V	+ Improved IEEE 1609.4 channel utilization and throughput + Channel access based on priority (safety message QoS transmissions)	- No guarantee on improving non-safety transmission throughput - Updated information lists not used to keep other nodes aware of the channels’ status

Table 3-1. MAC protocols for VCNs – advantages and disadvantages (Continuation).

PROTOCOL	Comm. Type	Advantages	Disadvantages
C-MAC (KIM, LEE, LEE, 2016)	V2I	+ Lowered collision probability of safety messages + Improved safety packet delay performance in dynamic environment	- Fixed time slot selection for random safety event is not robust
EDCA-RES WAVE (KIM [et al.], 2017)	V2V V2I	+ Contention-free scheme on the SCHs through reservation (non-safety applications) + Improved reliability of broadcasted safety packets by RSU ACK	- CSMA/CA based - Every OBU has dual radios (additional transceiver)
sdnMAC (LUO [et al.], 2018)	V2V	+ Account of high mobility and dynamic vehicle densities (decoupling between control and data plane)	- Not a multi-channel MAC protocol - Fixed frame length not adequate to both sparse and dense mobility scenarios
STMAC (JEONG [et al.], 2018)	V2V V2I	+ Hybrid protocol with spatio-temporal coordination (reliable safety message transmission) + Multiple vehicles can transmit in the same time slot	- Non-safety services requiring high data throughput not supported. - Vehicles registration is needed and limited to intersections

3.2 IEEE 802.11

The IEEE 802.11 standard (centralized or ad hoc) is often used to implement VANET prototypes due to large availability of inexpensive 802.11-based wireless devices. In general, there is minimal frame exchange: a frame sent from the source station and an acknowledgment sent from the destination station to inform the frame was received correctly. When the acknowledgment is not received by the source, it tries to transmit again using the basic access mechanism. The protocol uses the distributed coordination function (DCF) which is responsible for medium access and is based in CSMA/CA (CSMA with collision avoidance). To sense if the medium is idle *physical carrier sensing*, based on hardware, can be used but it cannot overcome the hidden terminal problem. Instead, *virtual carrier sensing* is used and it is based in network allocation vector (NAV) which is a timer indicating for how long the medium is busy. The medium access in VANETs using 802.11 in ad hoc mode is based on RTS/CTS/ACK packets. A vehicle, after sensing the medium idle for the time correspondent to Distributed Inter-frame Spacing (DIFS), sends a RTS with its identification and duration of the whole transmission. All neighbors set their NAV accordingly. If the receiver is ready, it waits for the time correspondent to Short Inter-frame Spacing (SIFS) and sends the CTS with transmission duration. All neighbors (of receiver) set their NAV accordingly. After receiving the CTS, the sender waits for SIFS and starts data transmission. The receiver, after successfully receiving the data frame, waits for SIFS and sends the ACK only for the sender and both set their NAV to 0. The basic DCF access method, in which a station uses DIFS, is shown in Figure 3-1.

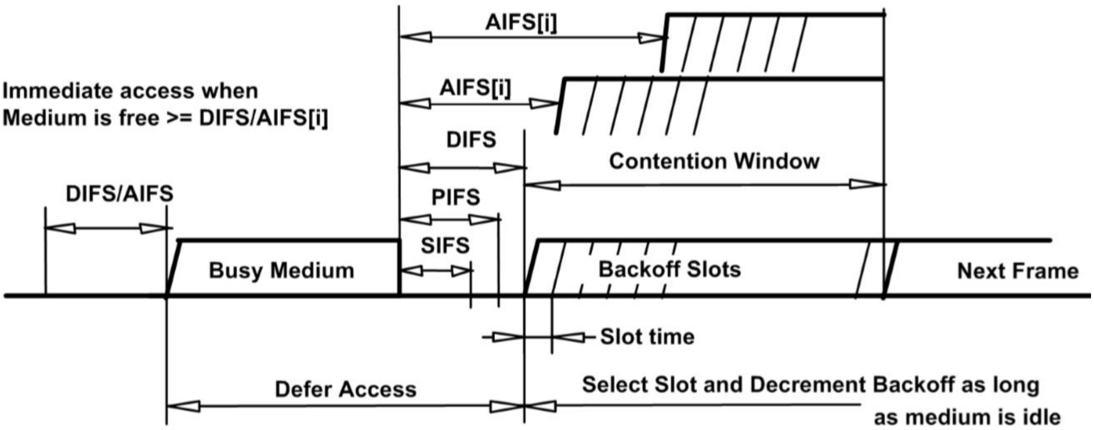

Figure 3-1. Basic DCF access method where DIFS is used (from (IEEE 802.11, 2007)).

Access to the channel in a timely and predictable manner is needed in order to meet a bounded real-time deadline. If a CSMA based method is used, since adaptive transfer rate can't be used due to the lack of ACK feedbacks, an increase in the number of nodes will result in more simultaneous transmissions, which will lead to decreased packet reception probability and excessive channel access delay, thus jeopardizing road traffic safety applications requiring upper bounded access delay and guaranteed message delivery. In addition, the typical broadcast-based applications used in VANETs affects 802.11 ability to recover from collisions since there are no ACKs and the backoff procedure is invoked, at most, only once during the initial carrier sensing, therefore losing the advantage of increasing the Contention Window (CW) to augment the number of backoff values.

The main argument for CSMA is that VANETs rarely experience high network loads, and traffic smoothing techniques can be used to keep data traffic acceptable. However, such techniques are commonly used in centralized networks (and only reduce the average delay) or geographically restricted networks, neither of which is applicable to VANETs, due to their highly dynamic nature. As so, the problem with unbounded worst-case delay still remains. Also, when using the original CSMA algorithm, hidden terminal situations may occur in centralized networks using an AP. This is due to collisions at the only receiver, which may be attenuated using RTS/CTS control packets, or in ad hoc networks independently of the MAC algorithm used. However, in the context of a VANET where a safety message is broadcasted, it may not be very harmful since there is more than one intended receiver and it is not likely that all nodes experience problems. Moreover, due to high vehicles' mobility, it is possible that following broadcasts are received in perfect conditions, by the nodes experiencing problems in the prior transmission of the safety message. Also, due to 5.9 GHz band usage and multipath/diffraction characteristics, it is more likely that hidden node's problem degrades performance in urban scenarios than in highways. It was shown in (SJOBERG, UHLEMANN, STRöM, 2011) that when considering a highway scenario, with a communication channel modeled as a fading channel, hidden terminal situations do not contribute for a major performance deterioration in terms of packet reception probability.

In conclusion, since the channel access procedure is random in CSMA, the channel access delay is not upper bounded and increases as the network load increases. Therefore, CSMA is not a time-predictable MAC method, making it not suitable for real-time traffic. Also, it is not scalable.

3.3 WAVE MAC Protocol

The WAVE MAC protocol was developed for the requirements coming mainly from active safety applications, where reliability and low latency are very important. It relies in a basic MAC and an extension MAC layer. The basic MAC is the IEEE 802.11 DCF based in CSMA/CA and uses Request-To-Send/Clear-To-Send (RTS/CTS) and Network Allocation Vector (NAV). The extension MAC layer uses the Enhanced Distributed Channel Access (EDCA) mechanism originally provided by IEEE 802.11e QoS amendment. The mechanism is based on the basic CSMA.

Together, the channel access process for both the control channel and service channels includes listen before talk (LBT) and a random backoff, and allows prioritized channel access. The backoff consists of a fixed and a random waiting time. The fixed waiting time is a number of "slots" given by the parameter Arbitration Inter-Frame Space (AIFS), as it can be seen in Figure 3-1.

When using EDCA, and consequently access categories (ACs), the duration of the fixed waiting time AIFS is dependent on the specific value of the parameter AIFSN (AIFS number), which is related with the AC of the node. For non-AP stations its value should be greater than or equal to two, whereas for APs the value of AIFSN is greater than or equal to one. The relation among AIFS, AIFSN, DIFS and slot times immediately following a medium busy condition is shown in Figure 3-2. In this example, assuming AIFSN = 2, the medium access function allows transmission after aSIFSTime+2·aSlotTime (if one assumes that the backoff counter contained a value of zero). The timings aSIFSTime and aSlotTime are fixed per PHY layer used. In Figure 3-2 is also shown the case where the initial value of the backoff counter is one, with the correspondent transmission time occurring after one additional slot time when compared with the example where the backoff counter is zero.

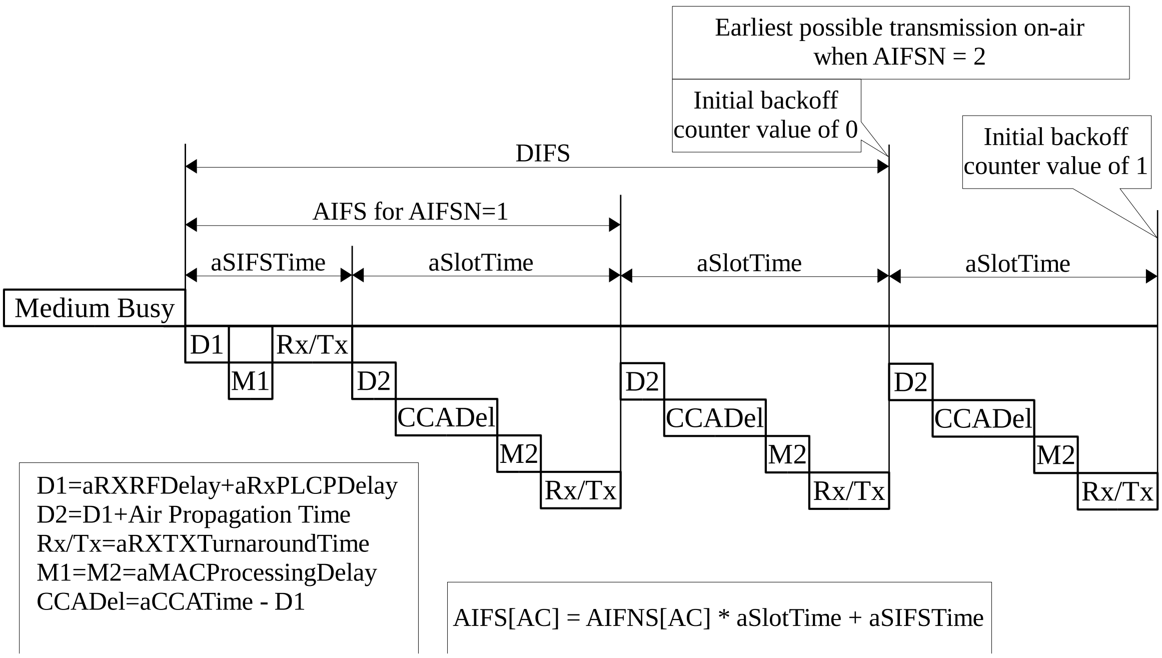

Figure 3-2. Channel access process of IEEE P1609.4/IEEE 802.11p MAC (redrawn from (IEEE 802.11, 2007)).

The random waiting time is also a number of slots, but the factor is drawn from a contention window. The initial size of the CW is given by the factor CW_{min}. Each time a transmission attempt fails the CW size is doubled until reaching the size given by the parameter CW_{max} (EICHLER, 2007). In broadcast mode the CW is always set to CW_{min} and is never doubled. The messages' priority is provided using different channel access parameters (AIFS and CW), within four ACs: background, best effort, voice and video (lowest to highest priority respectively). Therefore, within the MAC layer there are two contention levels. First the packet contends internally (based on ACs) for selecting which packet will be transmitted (Figure 3-3), and secondly the chosen packet will contend externally using the channel access parameters. Since it is a contention based mechanism, the performance on supporting throughput sensitive applications in densely populated scenarios can be improved.

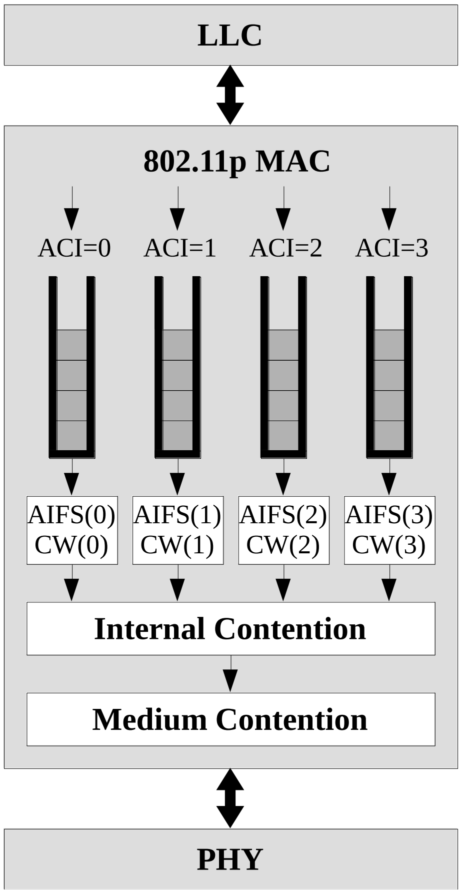

Figure 3-3. Prioritized access for data transmission on one channel (adapted from (IEEE WAVE, 2010)).

Using 802.11p MAC, the most frequent case of simultaneous transmissions leading to collisions occurs when the nodes reach a backoff value of zero. Since the number of values available to randomly select from, when the backoff procedure is invoked, is smaller for higher priority classes, the probability of simultaneous transmissions in such classes is higher. The IEEE 802.11e EDCA scheme was also subject to performance analysis in several other works. Although there are also existing proposals on improving the performance of IEEE 802.11e, they cannot eliminate the intrinsic shortcoming of IEEE 802.11e, which is that it only supports “statistical” priority for specific flows but not “strict” priority for individual packets.

There are several works in which the IEEE 802.11p MAC method was studied in terms of real-time performance. In (BILSTRUP, 2009), simulations using a realistic highway scenario showed that vehicles using 802.11p MAC method (CSMA/CA) can experience unacceptable channel access delays, thus meaning this MAC method does not support real-time communications. Also, in (KHAIRNAR, PRADHAN, 2013) the DSRC/IEEE 802.11p MAC method was simulated on a highway road scenario with periodic broadcast of packets in V2V situation. The simulation results show that a specific vehicle is forced to drop over 80% of its messages because it could not get access to the channel before the next message was generated.

3.4 ADHOC MAC

ADHOC MAC (BORGONOVO [et al.], 2004) was designed within the European project CarTALK2000 and is based in the Reliable R-ALOHA (RR-ALOHA) protocol, which extends the Reservation ALOHA (R-ALOHA) to achieve a dynamic TDMA mechanism in a distributed way, where each active vehicle needs to select for itself one single-hop broadcast channel (so-called BCH). This BCH is one time slot periodically repeated in successive frames (each with N time slots).

To overcome the hidden terminal problem, each vehicle sends on its BCH its frame information (FI), which is a vector with N entries that indicate how were sensed the status of the previous N time slots in the previous frame. When a vehicle hears a successful transmission on some time slots, it marks in his FI (Frame Information) field the corresponding entries with the transmitter identification corresponding to a reserved and busy slot. A new vehicle listens during one time frame before attempting to transmit on a free time slot. Then, if in the next time frame the corresponding time slot (where a transmission was tried) is marked by its identification in the whole received FIs, it means that the time slot is reserved for it in the two-hop neighborhood. The periodic propagation of the FI lets terminals know the entire ongoing transmissions in a two-hop neighborhood overcoming the hidden terminal problem, and thus reducing the transmission collisions.

A relatively good QoS is guaranteed by using the TDMA mechanism (time slot reservation in periodic repeated time frames) which is important for real-time traffic. However, the medium is not used efficiently and the number of vehicles must not be greater than the number of the time slots in the *superframe*. ADHOC MAC also requires time synchronization.

3.5 Mobile Slotted Aloha (MS-Aloha)

Precursor in using the time slotted oriented paradigm, Slotted Aloha (S-Aloha), which appeared in 1975, was the first approach from which all recent slotted approaches were derived from and refined till nowadays. MS-Aloha (SCOPIGNO, COZZETTI, 2009), specifically designed for VANETs, is a time slotted approach, which is well suited for safety message transmission, since channel access delay is upper bounded and fairness and scalability are features taken into account. MS-Aloha has been demonstrated through simulations to have outstanding results in very congested urban scenarios.

Nodes share a common synchronization source (e.g., GPS or Galileo receiver) and a common periodic frame structure divided into slots. A guard time is used between consecutive slots to account for propagation delays. The Frame Information (FI) field aims to propagate network information over 3 hops, preventing unintentional slot reuse and improving reception rate. A node infers the state of each slot by both direct sensing and by the correlation among received FIs (indirect channel perception). The own FI is then generated with the aggregated information. Each node flushes the information on slot *j* when the frame has reached again the position *j* (the information on slot allocation expires after a frame-time). This memory refresh time has been demonstrated to be long enough to avoid propagating information considered non-essential while getting an actual knowledge of wireless channel state.

Slot reuse is a presented feature to allow the admission of a higher number of nodes than slots available, without blocking. It should be carefully managed in order to minimize interferences. In MS-Aloha this is done based on received power rather than distance (as in STDMA).

MS-Aloha supports several priority flows by using pre-emption, thus increasing flexibility (ETSI, 2012).When a high priority message needs to be sent, and all slots are occupied, the node chooses a slot of lower priority and transmits simultaneously. The node transmitting the low priority message will get aware that the high priority flow have preempted the slot, by the on-going acknowledgments through information contained in all messages about how each slot is perceived (free, busy, collision). In this way, the high priority message is able to always gain access to the channel even in congested scenarios. In summary, it covers the features of scalability (effective slot reuse and non-blocking behavior) and reliability (connection-oriented paradigm and prevention of hidden terminals and unintentional slot reuse) by using mechanisms based on the knowledge of a PHY layer parameter (received power). As a downside it can be pointed the fact that this MAC method is tailored for pure VANETs (without infrastructure), and all nodes append a description about the state of all the slots (through FI), thus increasing message overhead. Also, synchronization is needed.

3.6 STDMA

Self-Organized Time Division Multiple Access (STDMA) (LANS, 1996), originally developed for the ship industry but adaptable for VANETs, is also a time slotted approach, which is well suited for safety message transmission since channel access delay is upper bounded and fairness and scalability are features taken into account.

The approach is specifically designed for position messages such as Cooperative Awareness Message (CAM). However, this MAC method is also tailored for VANETs (without infrastructure). In STDMA, the node transmitting in a slot specifies in the message the offset for the next used slot in the same frame. This avoids concurrent transmissions from temporarily hidden nodes due to natural wireless communication limitations (fading and shadowing).

The node divides the STDMA frame into a number of equal groups of slots. The length of each group is the number of slots elapsing on average between two consecutive transmissions. In each group there are only 20 % of the slots that the node is eligible to select from for transmission.

In this protocol each node is regularly forced to change the slot selected for transmission (by using a random integer time-out value). In this way, two nodes that were not at the communication range of each other when performing a slot choice, and have chosen the same slot, will not stay in a situation of potential transmission collision. This feature is used to cope with network topology changes.

The “pinching of the slot” is used when a node detects that all eligible slots are occupied. The selection of which slot to use for transmission is done based on the positions of other nodes. A node selects a transmission slot that is occupied by the node situated furthest away from itself. This allows dealing with overload situations and grants always access to the channel (scalable and predictable). Even so, it is possible to have unintentional slot reuse due to:

a) two nodes being close to each other (and having the same perception of free slots);

b) two nodes choose their slots before they were at the communication range of each other.

As seen, when using STDMA in vehicular environment vehicles will transmit regularly position messages, e.g. CAM, at a certain rate. These messages are needed for scheduling transmissions (choosing a slot) when all available slots are occupied.

3.7 Other MAC Schemes (specifically for safety message delivery)

In this section, some proposals made on MAC schemes for medium access, based on standard solutions, and specifically targeted for the delivery of safety messages in vehicular networks are described. Also, some studies are presented in what concerns coordination schemes between IEEE 802.11 Access Points (APs) in general, and specifically schemes using RSUs.

3.7.1 Vehicle-to-vehicle Safety Messaging in DSRC

Using as base the 5.9 GHz DSRC, the authors in (QING XU [et. al], 2004) focus on sending safety messages with high reliability and low delay for V2V communications without infrastructure (ad-hoc mode). The MAC layer designs are based on random access (to make dynamic allocation with TDMA, FDMA or CDMA, centralized control must be used). The communication type is broadcast and RTS/CTS messages are not used, contrarily to Multiple Access Collision Avoidance (MACA) protocol, proposed by Karn (KARN, 1990), which was an alternative to traditional CSMA, or the subsequent modified Media Access Protocol for Wireless LAN's (MACAW) (BHARGHAVAN [et al.], 1994).

Since 802.11a radios transmit over distances of 200 to 300 meters, it was proposed a single hop, local area communications service. When many receivers exist, or in a highly mobile network where the set of receivers can change a lot, receiver feedback is not appropriate. Therefore, this scheme evaluates ways to enhance reliability without receiver feedback. The various proposed options repeat each message without acknowledgement in combination with CSMA and its variants.

The safety messages have a useful lifetime corresponding to the delay requirement. Most safety messages produced by a vehicle are useful to many vehicles. Therefore a broadcast service is needed. At each transmitter the protocol evenly divides the message lifetime into n slots. Any random k ($1 \leq k \leq n$) slots are picked to repetitively transmit the message. The message fails if all transmissions are lost due to collisions. An overlay called MAC extension layer is used. Its role is to generate and remove repetitions. The system schedules the repetitions, which are events with a slot number. All these events ordered by slot numbers form a queue called the Packet Event Queue. Whenever MAC Extension receives a packet from MAC, if the message identification has not been seen before (new message), the message is passed up to the LLC. Otherwise, it is eliminated. Different MAC protocols were designed using the MAC Extension layer:

- Asynchronous Fixed Repetition (AFR): the protocol randomly selects k (initially configured) distinct slots among the total n slots in the lifetime. The packet is always repeated a fixed number of times, k. The radio does not listen to the channel before sending.
- Asynchronous p-persistent Repetition (APR): determines whether to transmit a packet in each of the n slots by flipping an independent unfair coin. The packet is transmitted if the result is head. The radio does not listen to the channel before sending.
- Synchronous Fixed Repetition (SFR): the same as AFR except that all the slots in all the nodes are synchronized to a global clock like slotted ALOHA.
- Synchronous p-persistent Repetition (SPR): the same as the APR except for the synchronization of transmissions by all nodes into common slots.
- Asynchronous Fixed Repetition with Carrier Sensing (AFR-CS): it has its own MAC. It generates the repetitions in the same way as in the AFR. Before transmission, the system checks the channel status using carrier sensing. If busy, the system drops the packet. If the channel is idle, the MAC passes the packet down to the PHY. When received a packet, the MAC checks the integrity of the packet, dropping it if it is corrupted.

- Asynchronous p-persistent Repetition with Carrier Sensing (APR-CS): similar to AFR-CS except that the slots are selected in the p-persistent manner.

This protocol uses a CSMA based medium access, with all the inherent problems already described in section 3.2. Random slots are chosen to transmit the message.

3.7.2 Distributed MAC Schemes for Emergency Message Dissemination in VANETs

The authors (PENG, CHENG, 2007) proposed a MAC scheme with a pulse-based control mechanism that uses a single control channel to achieve strict packet-level priority scheduling, in a fully distributed way to disseminate emergency messages. To deal with packet loss and the impossibility of using ARQ techniques, the MAC scheme sends duplicate copies of a message.

The proposed MAC scheme is assumed to coexist with the IEEE 802.11 MAC protocol, being the former used when emergency packets access the medium, and the latter used for non-emergency packets. The MAC scheme uses the so-called "*priopulses*", which are composed by an active part and a pause part of random length. During the active part single-frequency waves are transmitted in the control channel. The control channel carries only pulses, and pulses only appear in the control channel. All nodes monitor the control channel (even in the pulses pause) all the time except when transmitting. The application layer determines the message emergency level and puts it in the packet header, and determines the number of duplicate copies (to deal with the impossibility of using ARQ) to send for each message.

Priopulses ensure that a packet receives the actual priority it deserves for its level of emergency but also suppress the hidden terminals when a message is in transmission. Each priopulse has an active part (fixed length) and a pause part (a contention window of fixed size subwindows and a residual pause of *random* length). The active part suppresses hidden terminals and delivers the emergency level information (a longer active part indicates higher level of emergency). Such encoding is more robust against loss than placing the level information in the message itself, and priopulses are more tolerant to interference than bit-based messages since priority information is related only with the length of the priopulse. The random pause part is to support multiple levels of priority. If two sources of the same level draw similar delays a collision may result. The random length of the residual pause is designed to deal with this problem. The active part of the first priopulses is synchronized but the random length pause will desynchronize the next active parts. After desynchronizing, one source will detect the other (hear its priopulse) and back out. After that, the message will be successfully disseminated since multiple copies of the message are sent in this scheme. Priopulses are relayed (spread) to suppress hidden terminals of the message source. A priopulse triggers its relaying nodes to regenerate it as soon as it emerges in the control channel. If the coarse synchronization between sender and its receivers is lost (interference or noise), the sender will detect pulses in its own pauses and thus stop transmission in both channels. The nodes start contending for the medium after interference/noise disappears.

As downsides, this scheme needs two MAC protocols, one for emergency messages and other for non-emergency packets. The emergency level information only has a single and short presence in the data channel (in a corresponding message field). In contrast, in the control channel, the emergency level information exists as long as an emergency message is in transmission. This is because a node continuously transmits priopulses in the control channel while using the data channel for disseminating emergency packets.

In the work of (ZHANG, SU, CHEN, 2006), an analytical model was proposed to analyze transmission delay and successful delivery rate of safety messages. Vehicles close to each other form a cluster. The proposal uses three different protocols for different functionalities. The first is contention based and is used to perform cluster management tasks. The second is responsible for the exchange of both safety and non-safety messages. The third protocol is used to arbitrate the communications between the cluster head and cluster member vehicles within a given cluster. The scheme needs two radio devices per vehicle, and has high overhead with a complex algorithm.

The authors (BHARATI, ZHUANG, 2013) focused on cooperative communication to enhance reliability of communication links in VANETs. It is presented a cooperative MAC scheme, referred as Cooperative ADHOC MAC (CAH-MAC), in which neighboring vehicles cooperate by utilizing unreserved time slots for retransmission of packets that failed to reach the intended receiver, due to a poor channel condition. The probability of successful packet transmission is increased, but a limited number of vehicles can be handled and large overhead is needed.

3.7.3 Coordination Schemes for IEEE 802.11 APs

A regular AP of IEEE 802.11 performs similar functions to those that can be thought for a RSU. Examples include storing data to deliver it later to other stations, or scheduling. In this sense, a parallelism can be drawn between a RSU and an AP of IEEE 802.11. Various authors have proposed coordination schemes between IEEE 802.11 APs. In (VERGADOS, VERGADOS, 2004), it was introduced an intra-access point synchronization scheme to allow cooperation between APs whilst providing guaranteed QoS using Point Coordination Function (PCF). PCF provides low delay and jitter, while allowing a fair bandwidth sharing. However, their scheme suffers from scalability issues.

Another important issue was taken in account in (RAMANI, SAVAGE, 2005); they proposed a solution called SynScan, which was a practical fast handoff scheme between 802.11 APs for infrastructure networks, reducing delays in the handoff process. In (CHUI, YUE, 2006), the authors extended the scheme of (RAMANI, SAVAGE, 2005) in order to solve the problem of beacon collision between APs. APs have to be synchronized in order to transmit their beacons one after the others in the same channel, allowing mobile stations to get the beacons of available APs in the same channel. In (ZHAO, 2006) it was proposed a coordination method between APs for 802.11 mesh networks, to improve the throughput fairness for stations in different Basic Service Sets (BSS) of an infrastructure based WLAN network. Despite having some related concepts (e.g., preventing beacon collision between APs), none of these proposals are specific to WAVE or a related scheme.

In (VALEIRO [et al.], 2008), the authors show that a new feature from 3GPP Release 6, multimedia broadcast/multimedia services (MBMS) is able to provide I2V services efficiently on top of the UMTS network. In (SANTA, GOMEZ-SKARMETA, SÁNCHEZ-ARTIGAS, 2007) the authors go even further and propose a unified V2I and V2V architecture using UMTS, claiming that when the High Speed Packet Access (HSPA) technology is fully functional, latency times will be small enough to allow V2V safety applications. They define a peer to peer approach over cellular network, organizing vehicles in different traffic zones or clusters, where each vehicle communicates with a roadside entity responsible for that traffic zone. However, tests with current UMTS technology showed insufficient results for message propagation delay between vehicles.

3.7.4 Schemes Using RSUs (Road Side Units)

Real-world scenarios often require the use of multiple RSUs, be it for covering wide geographical areas but also to cover the existence of natural or artificial obstacles, which usually put at risk proper communications. Some of the following summarized works seem to support that using RSUs is a feasible option to disseminate safety messages. The use of RSUs provide a reliable alternative to V2V communication, particularly in accident-prone areas or areas where vehicle traffic is sparse or even suburban areas with heavy traffic. In addition, the use of RSUs allows the management of medium access.

In 2013, the authors (ALI, CHAN, 2013) looked at the issue of using RSUs for data dissemination in VANETs in order to assist V2V frequent disconnection problem. If a RSU is overloaded with requests, it may experience high deadline miss rate. Ali and Chan proposed a multiple-RSU model in which the RSUs are interconnected, know the workload information of each other and can exchange high volume workload, to transfer some of its delay tolerant requests to RSUs which have light workload and are located in the direction the vehicle is heading. Their simulation results shown the multiple-RSU model outperforms the single RSU model significantly in terms of deadline miss rate, average response time and average stretch (servicing efficiency measure). They have used the IEEE 802.11 MAC layer implementation. This work was focused on delay tolerant requests and is not directly related with safety messages. The authors assumed VANETs services are provided to vehicles at hot spots (e.g., gas stations or road intersections), where the density of vehicles is typically higher than other areas.

The authors (LIU [et al.], 2011) presented a RSU-Assisted Multi-channel Coordination (RAMC) MAC protocol that fully utilizes all channels in order to provide safety and non-safety data communication using RSUs. They state that under high traffic densities, the service channels are often completely idle while the control channel is congested. The RSU monitors the control and service channels simultaneously to receive and analyze all the safety messages. Then, periodically, it broadcasts an aggregated traffic view report to warn all neighboring vehicles in all channels, allowing service channel users to maintain adequate and timely safety awareness. The simulation results showed that the RAMC protocol consistently achieves very high percentage of non-safety usage while maintaining high safety message delivery ratios. It is not specified how the hazard is detected but the authors assume that the information is transmitted on the safety channel. Time synchronization is also needed.

In (SOU, TONGUZ, 2011) the authors state that studies have shown that sparse vehicle traffic leads to network fragmentation, which poses a crucial research challenge for safety applications that try to disseminate a warning message, from the source vehicle to other drivers, before they reach the potential danger zone on the road. The authors have analyzed and quantified the improvement in VANET connectivity on highways when a limited number of RSUs are deployed. Their results showed that even with a small number of RSUs, the performance in terms of the probability of network connectivity, the re-healing delay (delay that incurs in delivering messages between disconnected vehicles), and the message penetration time can be significantly improved in highway VANET scenarios. On a 300-km highway, for example, the re-healing delay is reduced by 70%, whereas the average number of rehealing hops is reduced by 68.4% when deploying 50 RSUs compared to an operation with no RSUs. Therefore, deploying a small number of RSUs can achieve a substantial improvement when the vehicular network is sparse.

In (BERLIN, ANAND, 2014) the authors elaborate on the transmission of fixed road hazard (e.g., tree or boulder fall) messages in highways with the use of smart RSUs (Direction based Hazard Routing Protocol – DHRP). This was due to the assumption of sparse highway traffic, in which case the vehicle encountering the hazard is likely to be the primary source of information. Thus, V2V would not be feasible since vehicular traffic is not dense enough. It is highlighted that the majority of research have been focused on developing protocols and methodologies, in what concerns safety message dissemination, using V2V communication, but this pre-supposes that vehicular traffic is high enough. However, the authors state that the concepts of storing and selective forwarding of safety messages are important and need also to be considered in highway scenarios with sparse population of vehicles. Their simulation results for the DHRP performance show that by using RSUs to disseminate road hazard messages, the network overhead is highly reduced and high reliability can be achieved.

The authors (MEIRELES, FONSECA, FERREIRA, 2015) propose the so-called Vehicular Flexible Time-Triggered (V-FTT) MAC protocol, which is a deterministic MAC protocol, based in the flexible time-triggered (FTT) paradigm, that focuses on providing real-time guarantees in a vehicular environment. It uses the multi-master multi-slave spatial TDMA, in which a configurable number of RSUs act as masters and schedule the transmissions of several OBUs. The protocol inherits most of its concepts from the original FTT protocol definition. It also adopts redundant scheduling for OBUs transmissions in order to increase reliability, and to cope with different propagation patterns by RSUs due to environment aspects. RSUs cooperate to schedule OBUs safety communications, and thus coordinate between each other to avoid undesired interferences. This protocol demands that OBUs register themselves with a RSU prior to sending periodic messages (e.g., CAM) or safety-related messages, although non-registered OBUs will also receive safety information from RSUs.

In (KHAN, PEDREIRAS, FERREIRA, 2014) it is presented a proposal for scheduling safety messages based on the Vehicular Time Triggered protocol. The authors present an analytic framework that enables managing the traffic appropriately. It is adopted a realistic scenario with multiple RSUs and used a protocol interference model (communication between two nodes is successful if there are no concurrent transmissions in a predefined interference range of receiver node) instead of the physical interference model. A node assignment scheme is adopted in order to derive a schedule that guarantees a conflict free node transmission, and slot reutilization is also adopted in order to increase the number of vehicles in the system. The proposed scheduling policy aims to increase the reliability of safety messages' transmission by adopting redundant scheduling while minimizing its impact on the bandwidth utilization. As a downside, vehicles' registration when entering on a safety zone is needed. Although non-registered OBUs will also receive safety information, they are not able to transmit information according to the proposed protocol, and they should contend for transmission during the free period without any guarantees. Also, OBUs have sessions that need to be changed between adjacent RSUs.

The authors (YANG [et al.], 2008) proposed a road traffic information system which utilizes both inter-vehicle and infrastructure-based peer-to-peer communications. The system is organized as a two-tier hierarchical architecture where all vehicles broadcast traffic conditions over lower-tier vehicular ad-hoc networks. It is used the concept of a supernode or super-vehicle per cluster. By adding this extra layer, unnecessary V2V communications are reduced thus allowing better results in terms of delay for traffic information lookup and message exchange overhead. The protocol is not directed to safety messages and needs the super-vehicle management information to function properly.

The author (MILLER, 2008) proposes a hybrid architecture, adding V2I communications to the peer to peer approach, but considering that only a super-vehicle can carry out communications between the infrastructure and other vehicles in its cluster. In (CHENNIKARA-VARGHESE [et al.], 2007), the authors propose an extension of the local peer groups (LPG) concept for ad-hoc peer to peer networking of neighboring vehicles described by the authors in (CHEN, CHENNIKARA-VARGHESE, CAI, 2005): A LPG is a kind of cluster organization with two degrees of coordination: Intra-LPG communication supports near-instantaneous safety applications (100 ms latency) and Inter-LPG communication is used for applications that somehow extend the driver's view. We find again the same concept of super-vehicle described earlier, this time named group header (GH). The GH periodically broadcasts a Heartbeat (HB) message to other vehicles (Group Nodes (GN)) within the LPG. Also in (CHENNIKARA-VARGHESE [et al.], 2007), it was added the presence of RSUs and V2I communications. They assume that V2V and V2I communications use different channels. Depending on the RSU network architecture, RSUs can be an extension of LPG, assuming the role of GH, behaving like regular GNs or even performing as an inter-LPG relay. RSUs can also assist V2V communications in order to help established LPGs and help create new ones. In this type of schemes, there is the possibility of inter cluster interferences, and some kind of complexity is added for cluster organization and management.

3.7.5 Token Passing MAC for Platooning

In (BALADOR [et al.], 2015) the authors focused on the challenging field of platooning. The strict timing requirements imposed by the distributed control system are taken into account, not by using TDMA on top of IEEE 802.11p, as many ongoing research suggests, because it requires synchronization and flexibility (using different beacon frequencies), but by using a token-passing medium access method. The next token holder is selected based on beacon data age to allow beacons to be re-broadcasted in each beacon interval whenever time and bandwidth are available.

The authors state their method is able to reduce the data age, and to considerable increase reliability when compared to pure IEEE 802.11p. This method is compared with pure IEEE 802.11p and not with TDMA on top of IEEE 802.11p, which also presents some advantages. Moreover, the authors argue that for platooning the use of a separate service channel, with an additional transceiver, is a requirement for the specific type of envisaged application, in which beacon update periods of 20 ms are often mentioned.

3.7.6 VeMAC

In (OMAR, ZHUANG, LI, 2013) the authors proposed a TDMA-based scheme aiming to improve the QoS of safety packets, which depends directly on collisions, delay, and system throughput. The scheme improves the hidden node disputes among nodes and also RSUs. The nodes access time slots on the CCH primarily by initiating a collision-detection process. Each node randomly chooses a time slot and checks if any of the neighboring nodes, within two hops, simultaneously attempt to acquire the same time slot. If at least one of those nodes try to access the same time slot, then a collision will be detected. Every transmission is acknowledged implicitly by listening to the following transmissions, and this provides a reliable broadcast. One of the disadvantages of VeMAC is the transmission of large control information over the CCH, resulting in greater overhead. Also, the proposed scheme does not consider the density of vehicles in either direction.

3.7.7 POCA-MCVN

In (CHU, FENG, LIN, 2015) the authors proposed a prioritized optimal channel allocation (POCA) scheme based on the concept of cognitive radio (CR) for multi-channel vehicular networks (MCVN). The aim of POCA is oriented toward improving the throughput and reliability of data transmissions. POCA adopts a modified EDCA scheme by assigning high-priority ACs to the so-called primary providers and low priority ACs to the so-called secondary providers. The scheme is mainly safety service–oriented, and there is no guarantee on improving non-safety transmission throughput delivered by secondary providers. Moreover, the scheme does not mention any use of updated information lists to keep other nodes aware of the channels’ status.

3.7.8 C-MAC

In (KIM, LEE, LEE, 2016) the authors proposed the scheme emphasizes on following a contention-free broadcasting approach for safety services by utilizing RSU for coordination purpose. The proposed coordinated multi-channel MAC protocol for VANETs (C-MAC) allows the vehicles entering the RSU coverage to reserve CCH during the SCH interval utilizing dynamic frame-slotted ALOHA (DFSA). Furthermore, the RSU coordinates the transmission order of the safety messages from reservation information. In terms of limitations, the scheme assumes that a vehicle can only transmit an event-driven safety message during its reserved time. However, a fixed time slot selection for random safety event is considered to not be robust.

The analysis given above for the protocols from section 3.7.6 to 3.7.8 is based on the review of (RASOOL, ZIKRIA, KIM, 2017).

3.7.9 EDCA-RES WAVE

In (KIM [et al.], 2017) the authors propose an analytical model for the MAC protocol that consists of EDCA on the CCH and a reservation method on the SCHs for the WAVE standard. Specifically, a safety packet of a high priority and a request for service (RFS) of a low priority for the SCH reservation are serviced on the CCH with a contention-based EDCA mechanism; meanwhile, non-safety applications are serviced on a SCH with a contention-free scheme through the reservation of a SCH from the handshaking of an RFS packet on the CCH. In terms of drawbacks, it can be pointed out that the scheme is based on CSMA/CA and also that every OBU has dual radios (which means an additional transceiver).

3.7.10 sdnMAC

In (LUO [et al.], 2018) a software-defined radio approach is used. In existing TDMA-based MAC protocols, a node usually acquires slots based on what each node senses, meaning there is coupling of the control and data plane. This coupling makes the TDMA protocols unable to rapidly and agilely deal with the challenges in VANETs, such as high mobility and dynamic network densities. In terms of limitations, this is not a multi-channel MAC protocol, and a fixed frame length is not adequate to both sparse and dense mobility scenarios.

3.7.11 STMAC

In (JEONG [et al.], 2018) the authors propose a new hybrid MAC protocol using spatio-temporal coordination (STMAC) for urban scenarios for better wireless channel access in vehicular networks. The objective of STMAC is to support reliable and fast data exchange among vehicles for driving safety via the coordination of vehicular infrastructure, such as RSUs. STMAC allows that multiple vehicles can transmit in the same time slot without channel interferences or collisions by utilizing directional antennas and transmission power control. The PCF mode is used to register vehicles for a time slot allocation as well as an emergency message dissemination from an RSU to vehicles. It uses the DCF mode for both safety message exchange and emergency message dissemination among vehicles by spatio-temporal coordination. In terms of limitations, it can be seen that non-safety services requiring high data throughput is not supported. Also, vehicles registration is needed and the scheme is limited to intersections.

3.8 802.11 MAC DCF Performance Studies

The performance of the IEEE 802.11 MAC DCF using CSMA/CA protocol has been studied theoretically in several works. Most provide mathematical models confined to special cases such as single hop networks operating on a saturated assumption, which means that every node in the network has always a packet to send. The IEEE 802.11e EDCA scheme was also subject to performance analysis in several other works.

Bianchi was the pioneer in using a Markov process to model the saturation throughput analytically (BIANCHI, 2000). Wu et al. extend Bianchi’s model including the packet retransmission limit (WU [et al.], 2002). Others proposed refinements to those models but were all mainly focused on saturation throughput analysis.

In (VARDAKAS [et al.], 2007) an extensive end-to-end delay analysis was performed, based on Bianchi’s model, and including the queuing delay by using the M/G/1 queue. Already under any load condition, in (TICKOO, SRIKDAR, 2004) it is calculated the overall delay of a packet in a single-hop network by modeling the queue at every node as a G/G/1 queue. In (TICKOO, SRIKDAR, 2004), a mathematical model to estimate throughput and end-to-end delay is provided, including queue delay, over single-hop and multihop networks under any loading condition.

In (VASSIS, KORMENTZAS, 2005), an analytical model for delay performance evaluation of IEEE 802.11e EDCA scheme is presented, under finite load conditions for single-hop networks and considering that each station has only one access category index (ACI). The maximum allowable number of retransmissions is not taken into account.

In (HO [et al.], 2008), an analytical model for delay performance of 802.11e EDCA using two virtual collision handler (VCH) schemes is proposed. They extend the model used in (TANTRA, FOH, MNAOUER, 2005) to c queues for c different ACs. Both in (TANTRA, FOH, MNAOUER, 2005) and (HO [et al.], 2008) the saturation condition is assumed and they do not take into account the queuing delay. In (NEKOVEE, 2009), the associated bounds with packet delivery latency, of 802.11-based V2V protocols for rear-end collision avoidance applications, are precisely quantified.

The saturated model restricts the full study of the end-to-end delay performance since it does not consider the impact of the MAC layer queue. The end-to-end delay analysis of IEEE 802.11p/P1609.4 MAC protocol, including the specificity of control channel (CCH) and service channel (SCH) usage, under any loading condition, is an important issue to be addressed. In subsequent chapters of this thesis, the end-to-end delay of a specific WAVE MAC protocol is estimated, relying in V2V and V2I single-hop communication for timely delivery of safety messages.

3.9 Substantiation for the Thesis

In vehicular networks focusing on road traffic safety applications broadcast is the main transmission mode used by all nodes, and a decentralized topology with mobile nodes is used. Safety applications will benefit from the transmitted periodic position message (CAM) with an update rate of 1 Hz to 10 Hz. These messages will be the predominant data traffic present before full deployment of all suggested road traffic safety applications triggering hazard warnings, e.g. Decentralized Environmental Notification Message (DENM), reach full penetration. Thus, a continuous time-triggered data traffic model with broadcast should be the predominant model. A time slotted MAC approach is obviously very suitable for time-triggered CAMs, but it seems also an appropriate solution to guarantee timely delivery of event driven safety messages (events in vehicular networks are likely to affect more than one node simultaneously).

In (ETSI, 2012) it is stated that the loosely and single ad hoc approach of 802.11p makes impossible to match a RSUs to an AP, from a MAC layer perspective, since it would imply granting access to the network through authentication and association. This means that a RSU and an OBU are only differentiated at the higher layers. Although this is true, using a time slotted oriented approach on top of the 802.11p MAC protocol, where the RSUs assume a special role, similar to an AP, may be the most feasible solution in order to guarantee that safety-critical communication among vehicle users is performed within appropriate time bounds. There are several factors supporting this:

- Advantage can be taken of the already installed infrastructure without being dependent on the large design cycle of vehicles. The low rate of vehicle renewal will be an obstacle in most countries. A relatively easy deployment of infrastructure as done in (REGGIANI [et al.], 2013) is assumed feasible.
- It is likely that the evolution towards a fully connected vehicle environment will pass through a transitory period during which an increasing number of legacy vehicles (those equipped with communications outside the vehicle itself) will exist, in a similar manner of what happened with the GPS. GPS exists since the late 70's, but it took more than 20 years to start selling commercial applications, particularly the on-board GPS navigation system in vehicles. In the beginning of the century it was only usual to include this equipment in top vehicles. Only recently we start to see medium/bottom market vehicles including GPS trackers.
- By the same token, safety applications for vehicles may take as long as GPS to arrive to the market, probably longer because wireless technologies are not mature yet.
- Using RSUs can increase the range of communication by sending, receiving and forwarding data from one node to another, or benefit from their ability to process special applications forming V2I communication (RAPPAPORT, 2001). For instance, if traffic is congested in a specific highway zone, vehicles further behind without visual perception of the event may be informed by RSUs coordinating with each other and forwarding the information.

All of these factors favour infrastructure to vehicle communications instead of vehicle to vehicle communications. This means that the OBU will be equipped with a communication device, as already used in electronic toll collection, which will enable message dissemination through RSUs. Also, advantage is taken from the nowadays penetration of GPS devices in vehicles. Furthermore, this solution is somewhat resilient in the sense that safety event dissemination remains possible even in the case of a vehicle crashing and destroying its communication equipment, after the initial broadcast.

Therefore, V2I communication provides a good solution, particularly if the communication equipment is as easy and inexpensive to install in the vehicles, as the current equipment used for electronic tolls, and if a highway scenario is considered, as it is here. In summary, the thesis defended here states that a time slotted oriented approach to the 802.11p MAC protocol, with infrastructure, is the most feasible solution nowadays and in the near future, in order to guarantee that safety-critical communication between vehicle users is performed within appropriate time bounds.

Detailing a little further the thesis contributions, the first part comprises the detailed definition of the CCH interval as a slotted period. This is done as a mean to minimize transmission collisions. Two distinct periods are defined, a period reserved for coordination between adjacent RSUs and beacon transmission by those RSUs, and a period reserved for vehicle’s messages. These periods intend to timely deliver safety messages and provide vehicles with specific information in order to allow them performing an optimized slot choice. The slot utilization, in both periods is defined in detail in order to avoid, or at least minimize greatly the collision probability. An alternative solution, using only V2V based communications is also outlined to accommodate time-critical messages within WAVE, for safety applications in highways. This is for cases where full RSU coverage of the highway could not be possible, or the highway characteristics, such as tunnels, could limit the appropriate dissemination of safety messages.

The second part comprises the evaluation of protocol performance, particularly the MAC end-to-end delay, and compares this metric for two distinct situations. The first situation assumes that when a vehicle needs to transmit a message over the CCH (whether it is periodic data (beacons or WSAs), or an event-driven safety message), it will perform a random choice within the slots contained in the period reserved for vehicle’s messages. In the second situation, the vehicle uses a so-called position-based slot choice in order to perform message transmission. This choice is based on its current position (derived from the last GPS coordinate obtained), and based on information provided on the RSU beacon (RSU position, number of lanes, number of slots), which is sent in the beginning of every CCH interval.

The results, when analyzing several distinct cases, are improved significantly when using the position-based slot choice situation. When analyzing the total end-to-end delay, and considering a packet generation rate of 5 packets/s, a standard bit rate of 3 Mbps/s, a vehicles' velocity of 100 km/h, and a rush-hour situation, the delay is 207 ms for random slot choice versus 36 ms for a position-based slot choice (a reduction of about 83%).

CHAPTER 4

IMPROVED MAC TECHNIQUES

Summary

This chapter details improved MAC techniques, emphasizing the infrastructure-based MAC protocol advantages, as well as detailing the proposals for a safety-critical and bounded delay MAC protocol within a specific scenario. An alternative solution, relying solely in V2V-based communications is also proposed, for cases where the infrastructure may not be accessible (e.g., tunnels), or even not feasible to have total RSU coverage.

It is a fact that V2V communications are very promising and have a big potential. However, taking into account the world economic crisis along with slow vehicle renewal rate, V2V solutions may not be as close as intended, and are a somewhat distant scenario. As stated in 2013 by the technology market intelligence company, ABI Research, the V2V technology will gradually be introduced in new vehicles, resulting in a penetration rate of 61.8% by 2027. However, many envisioned safety applications that use multihop communications would only require a minimum market penetration rate of 10 percent or more (ERGEN, 2010). Even so, if every new vehicle was equipped with a V2V radio device starting from today, it will take more than two years before these applications could be functional on the road. Thus, it will take some time to be able to see the real safety benefits. As already referred in the previous chapter, a TDMA infrastructural solution, where RSUs take part in the network as a special element, is preferable.

In the following sections, it is assumed that the IEEE 1609.2 standard is also implemented, which means security services are used for all applications. Thus, data is not sensitive to security threats to the communication medium, and anonymity, authenticity and confidentiality are assumed as granted in every message. It should be mentioned that the solution proposed is easily extrapolated for the ITS-G5 standard.

4.1 The Macroscopic View of the I-TDMA (Infrastructure with TDMA Based Solution)

Taking as base the IEEE 802.11p MAC standard, the work presented in (FERREIRA, FONSECA, GOMES, 2008) used the fundamental assumption that non-enabled and enabled vehicles would coexist in the first stage of the technology growth. The enabled vehicles, equipped with OBUs are able to communicate with other enabled vehicles and RSUs. Focusing on an already deployed infrastructure, the highway (or at least the accident-prone areas) is assumed to be fully covered by several RSUs, deployed by the respective operator.

As already mentioned in Section 3.1, the defined parameter set of EDCA is capable of prioritizing messages. However, with the increasing number of nodes sending messages of highest Access Category (AC), the collision probability increases significantly (EICHLER, 2007). In densely populated scenarios or in case of filled MAC queues, native IEEE 802.11 MAC cannot ensure time-critical message dissemination. Proposals found in the literature are to integrate a re-evaluation mechanism for messages to continuously reduce the number of high priority messages and prevent long queues. In addition, the use of different EDCA parameters could mitigate the high collision probability. To reduce the number of high priority messages, it would seem appropriate the definition of a new AC (so-called “Safety AC”) within EDCA, reserved for collision and hard braking warning messages (it is not likely to exist several of these simultaneously), where the AIFS along with the CW value should be less than the AIFS of video AC. In this case it would be guaranteed that no contention between those messages and video AC messages would occur. However, this would not comply with the IEEE 802.11p standard.

Taking into consideration the above mentioned, the approach here is to use a slotted based solution, with beacons transmitted by RSUs, to adequately reduce the collision probability in V2I (initial broadcast after a safety event) and I2V (rebroadcast in the target area by RSUs) communications. The idea, depicted in Figure 4-1, is to have RSUs coordinating the rebroadcasting of safety messages with bounded delay and no contention in the target area.

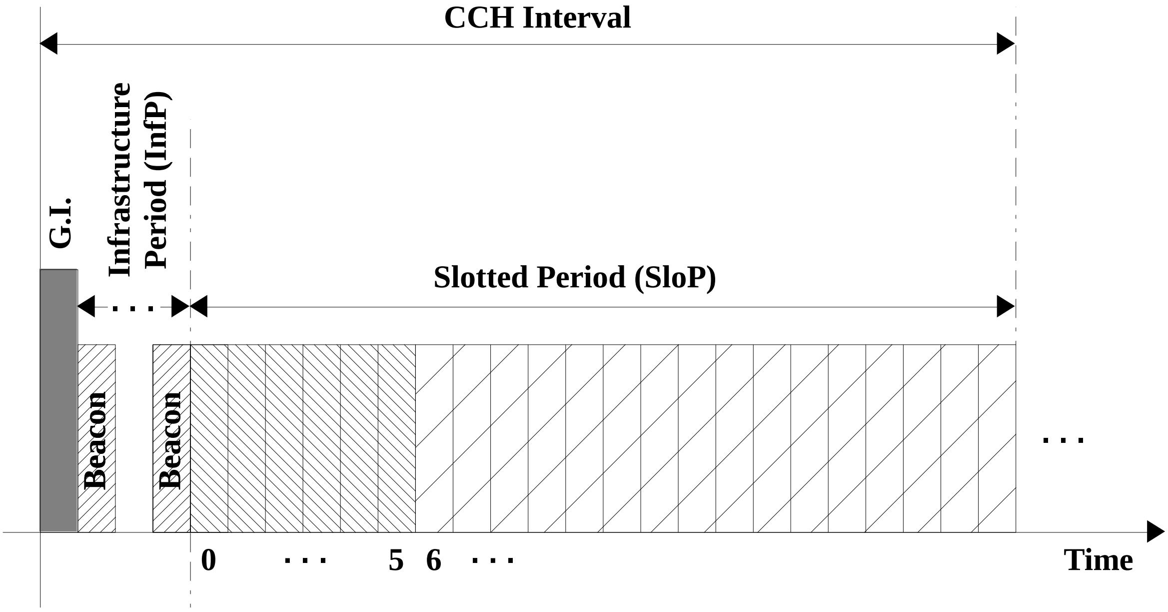

Figure 4-1. Slotted based approach with beacons.

The intended way to organize every control channel (CCH) interval is to divide it into an Infrastructure Period (InfP) and a Slotted Period (SloP). The former is reserved for coordination between RSUs, and for beacon transmission. In this period all vehicles should listen to the channel. Regarding the SloP, the initial six slots are reserved for RSUs and are used by them if there are safety messages to rebroadcast. A safety message may need to be rebroadcasted by two adjacent RSUs depending on the target area of the message (distance intended to disseminate the warning from the safety event location). Each RSU uses one time slot for each event. The RSUs' beacon contains general information, such as the position of the RSU, and also information about the possible slots allocated by RSUs within SloP. The remainder of SloP (from slot 6 onwards until the end of CCH interval in Figure 4-1) is considered free and available to vehicles wishing to send messages (periodic or event-driven). Vehicles that generate an event broadcast the corresponding message on an empty slot (it should be noted that vehicles have knowledge of SloP occupation by listening the beacons in the beginning of the CCH interval). The RSUs will know the time the event was triggered and, by using beacons, will inform in the next CCH interval the specific slots being used to rebroadcast the message.

By using this solution another advantage arises. Considering a vehicle brakes suddenly (generating an event), and after that collides destroying the communication equipment. In this case, the event will still be disseminated by RSUs despite the event originator cannot communicate further. The detailed definition of the coordination between adjacent RSUs, whose coverage areas are overlapped, is done on the following chapter. The Infrastructure Period duration is still dependent on the infrastructure deployment.

4.2 Precise Definition of I-TDMA

This section addresses the issue of beacon coordination between adjacent RSUs, as well as a mechanism for the retransmission of a safety message by such RSUs.

As referred in section 4.1., the RSUs play a major role in rebroadcasting warning messages adequately, i.e. avoiding contention in order to timely deliver the messages. Therefore, a critical issue is the coordination between RSUs. Recall that the aforementioned solution was made in order to fully handle the problem of uploading (V2I) safety critical messages that could contend for the medium, and the problem of guaranteeing that the safety information arrives to the vehicle (I2V) within a specified time bound.

Taking into account the CCH interval organization defined previously, which can be seen in Figure 4-1, every CCH interval is divided into an Infrastructure Period – reserved for RSUs coordination and for beacon transmission by RSUs – and a Slotted Period – where the initial part is used by the RSUs for rebroadcasting safety messages, and the remainder is used as a contention period for short status messages, WSAs and safety event-driven messages. Using the Infrastructure Period for RSUs’ beacons may intuit us to use the SloP with a defined slot schedule done by RSUs, and informed within their beacons, for vehicle's utilization. However, this would require some kind of register/association, and the standard explicitly defines there is no association procedure in a WAVE context (IEEE 802.11.p, 2010). More importantly, it could jeopardize the timing requirements since the vehicle would first have to "register" itself, and only in the following CCH interval transmit a safety message within its reserved slot. Thus, vehicles access the SloP ideally using a deterministic slot choice instead of random access, in order to minimize transmission collisions, without any need for association nor schedule done by RSUs (detailed in section 4.2.3).

The first part of this section is concerned with the Infrastructure Period organization and how the RSUs will coordinate with each other in order to rebroadcast safety messages adequately. So, the focus here is only in the I2V message dissemination. The issue of slot selection for the initial broadcast (V2I) by the vehicle generating the event will be analyzed in detail in Section 4.2.3.

The message target distance, d_{mt}, can be used to define the number of adjacent RSUs that will rebroadcast such message. Assuming the RSUs have a coverage range of d_{cr} (radius), and each one is in the radio range from its adjacent, the total distance covered by n consecutive RSUs will be given by Eq. (4.1).

$$d_{mt} = (n+1) \cdot d_{cr} \tag{4.1}$$

Being the interest in safety-related applications, the distance covered by three RSUs, each with a typical transmission range of d_{cr} = 500 meters, is enough to disseminate the warning message and alert other drivers. This scenario is depicted in Figure 4-2. A safety message should be rebroadcasted by several consecutive synchronization intervals. Thus, each RSU participating in the rebroadcast procedure maintains a counter, n_{ret}, which is decremented by one in every retransmission (i.e., in every synchronization interval) until it reaches zero, meaning the end of retransmissions. The counter value is related with the message's lifetime, t_{lf}, which is the time a safety event must be rebroadcasted.

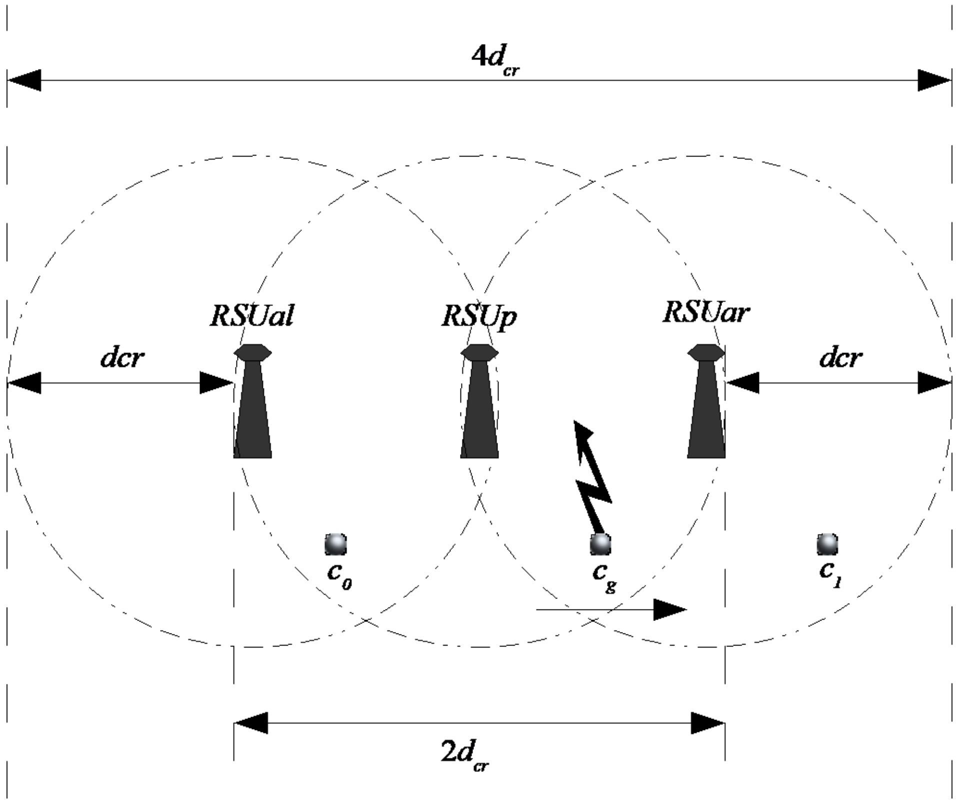

Figure 4-2. Three RSU coverage range.

We are considering the road in a similar way as used by road authorities and car rally races, i.e., the road position is a linear function starting in 0 and ending in the road length, D_{rl}, as seen in Figure 4-3.

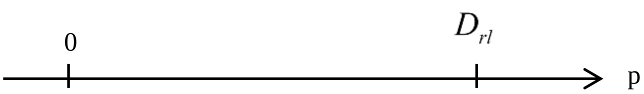

Figure 4-3. Road position (p) is a linear function.

Therefore, it is possible to know the driving direction information of a vehicle through two consecutive position measures, thus indicating if it is driving back or forward along the road (using Eq. (4.10)).

When the vehicle, denoted as c_g in Figure 4-2, is the only to generate and broadcast a safety message in a synchronization interval, the message will be received by the so called primary RSU (RSU_p), and by an adjacent RSU (RSU_{ar}). From both, the RSU_p will be the one to rebroadcast the message since RSU_{ar} detects that the vehicle is moving towards it by analyzing the driving direction information and vehicle position fields in vehicle's message. If, in the same synchronization interval, two other vehicles, one between RSU_{al} and RSU_p (C_0 in Figure 4-2), and the other ahead of RSU_{ar} (C_1 in Figure 4-2), also generate a safety event, this will lead to all those three RSUs having to rebroadcast the message. The beacon transmitted by each in the following Infrastructure Period contains information relative to the event ahead of each. In order to allow proper announcement of the safety events through the beacons, from all RSUs, contention must be avoided between them.

If the slot choice by RSUs was random, collisions would happen. These collisions would be caused by the same slot chosen by adjacent RSUs, or would be due to the hidden node problem, even if these RSUs are not at the communication range of each other (an example is shown in the following chapter). The following proposal is devised to cope with this issue. In summary, the Infrastructure Period will have five slots. The first three slots are used for coordination between RSUs. The last two slots are used for message dissemination through several adjacent RSUs.

4.2.1 Coordination for Beacons Transmission

Each RSU has a number corresponding to its sequence along the road. Also, there are sections identified by a number. Each section contains three RSUs and each RSU belongs only to one section (an example can be seen in Figure 4-4, from the start of the road, indicated by the arrow, and road direction from left to right).

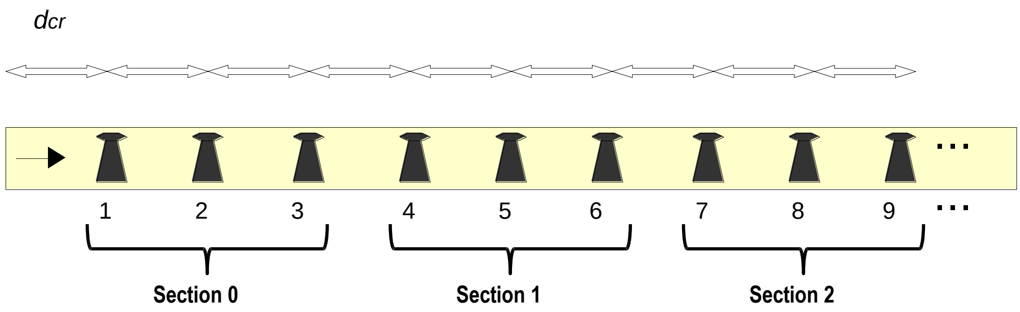

Figure 4-4. RSUs numbering and sections.

Although RSUs would benefit from a shared physical connection like a backbone network, e.g., taking advantage of the available optical fiber in some highways, it will be assumed here a more realistic scenario where such connection is not available. Instead, RSUs also use the WAVE technology to communicate with each other. Each RSU will use its InfP slot to transmit its beacon, whether it has listened or not a safety event broadcasted by a generator (OBU). This will allow minimizing the collision probability between vehicles broadcasting a message within SloP, as explained ahead. In order to avoid contention between adjacent RSUs, and to avoid hidden terminal collisions (e.g., RSU_1 and RSU_3 transmitting a beacon in the same InfP slot, and causing RSU_2 to hear a collision), each RSU chooses its InfP slot using its own number (RSU_{nr}) and its section number ($Section_{nr}$), as devised in Eq. (4.2).

$$InfP_{slot} = RSU_{nr} - (3 \times Section_{nr}) \tag{4.2}$$

This guarantees that all RSUs along the road will transmit their beacons without collisions. To verify the correct functioning when RSUs allocate slots according to the procedure explained above, Figure 4-5 shows the transmission slots used for the nine consecutive RSUs. In this case, no collisions will occur.

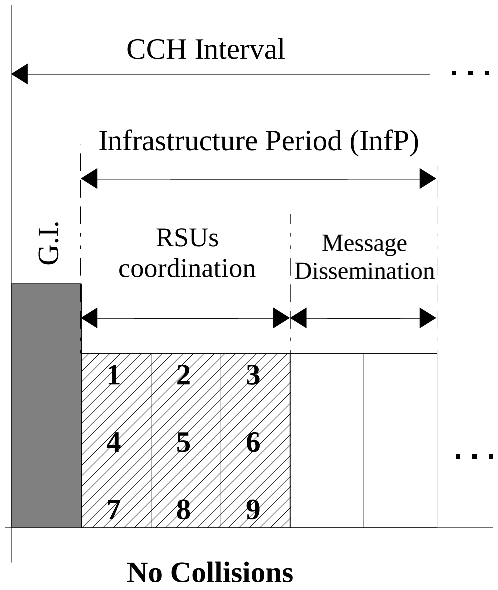

Figure 4-5. Infrastructure Period slot allocation by nine consecutive RSUs.

An example of an incorrect choice of slot allocation is shown in Figure 4-6. Although RSU_2 and RSU_4 are not in the communication range of each other, and thus do not listen each other's transmissions, if it happens that they choose randomly slot 2 to transmit a beacon, it will cause RSU_3 to listen a collision since it hears both beacons at the same time.

This is represented in the figure by surrounding RSU_3 with a ray type line. The same goes for RSU_6 and RSU_8 choosing slot 3 and causing RSU_7 to hear a collision.

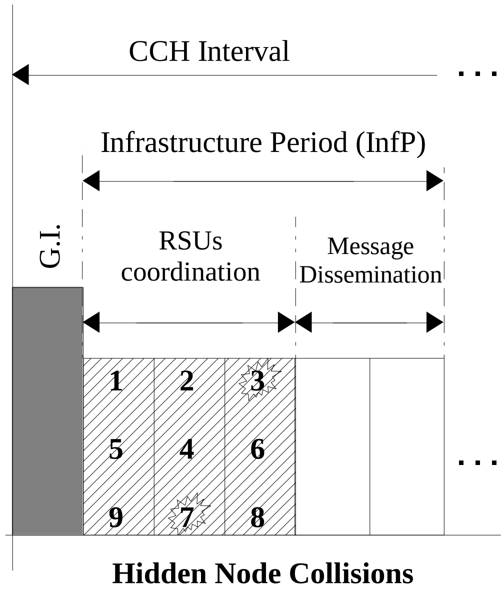

Figure 4-6. Incorrect choice of InfP slots lead to hidden node collisions.

Beacons are basically a WAVE Short Message from the WSMP within the WAVE protocol stack. As so, the information needed for protocol implementation will be contained in the Data field of the WSM. The data fields of beacons sent (Figure 4-7) are the following:

- "RSU Position" indicates the position of the RSU. It will be used by vehicles in the process of choosing a slot to transmit a message within SloP, when not using a random method. The number of bits needed for "RSU Position" is defined by GPS coordinates.
- "SlotsReserved" indicates how many and which slots are reserved in Slotted Period. Since each vehicle listens at most two RSUs simultaneously, and assuming each can rebroadcast three events, this field uses two bits defining how much slots are reserved, and three fields of eight bits each, defining the slot number used for the event. Thus, if the first two bits are 0 it means this is a pure beacon and no safety event has occurred, and the following fields are ignored.
- "AdjacentRebroadDist" contains a non-negative integer value, defined as n_{td}. It is used for message dissemination as explained below (Section 4.2.2).
- "VehiclePosition" contains the GPS coordinates in order to obtain vehicle's position in case of a safety message was received. A conversion from that to road position is done to get the vehicle position in road length (Figure 4-3).

- "VehicleDirection" indicates the direction the vehicle is travelling (f_i), in case a safety message was received.
- "NumberLanes" indicates the number of lanes in each direction of the highway. It will be used by vehicles in the process of choosing a slot to transmit a message within SloP, when not using a random method.

RSU Position (96 bits)	Slots Reserved (26 bits)	Adjacent RebroadDist (2 bits)	Vehicle Position (96 bits)	Vehicle Direction (1 bit)	Number Lanes (4 bits)

Figure 4-7. Beacon frame data fields (within WSM data field).

It is possible that two RSUs detect events that happened in an instant that leads to the scheduling of the transmission in the same reserved SloP slot. In this situation, and since each RSU listens the beacons from adjacent units, the one with a higher value for "VehiclePosition" will maintain its slot allocation within the SloP (if the vehicle is moving forward, relative to road direction, otherwise the one with lower value). The RSU determining that it will not maintain the current slot allocation will wait for the next infrastructure period in order to allocate other slot(s). This procedure gives higher priority for the event/vehicle which is ahead regarding the moving direction. This can be seen in Figure 4-9.

In alternative, a solution could be having each RSU allocating two slots for each event and using always the first of them, leaving the second for the RSU having the lower value of "VehiclePosition" in its beacon. However, this will lead to a poor utilization of medium resources since two events so close in time may have low probability of occurrence. In addition, a lower number of events could be dealt with. Dependently on the timing requirements of the safety application, if waiting for the next InfP to announce the event is time jeopardizing, the alternative solution could be forced.

4.2.2 Message Dissemination

After the initial broadcast done by the event generator, the corresponding safety message should be appropriately spread throughout the road. This is done by RSUs. The dissemination of the safety event is done by analyzing the "AdjacentRebroadDist" field in the beacon. When a RSU listens a beacon with an n_{td} value higher than zero, and infers it is behind the vehicle (relatively to the driving direction – this concept is illustrated in Figure 4-8, being RSU_1 behind the vehicle c_1) by examining the "VehiclePosition" and "VehicleDirection" fields, it will decrement n_{td} value by one and rebroadcast the message on an available slot. It will also send its beacon with the updated n_{td} value in the available of the two final slots of InfP (for each RSU rebroadcasting the message, one of these two slots will be used alternately for the respective beacon). This means that n_{td} is the number of RSUs, other than the originator RSU, retransmitting the message. It could be used to control the target distance of the message.

Although the GeoNetworking protocol (ETSI, 2011) does something similar to this, since it is very hard to make guarantees about network service qualities with its approach, it means that GeoNetworking is best suited to applications where messages are not time-critical. Also, GeoNetworking adds some overhead to packets for all applications. This can particularly jeopardize those applications with limited bandwidth channels, in which time-critical safety information is exchanged.

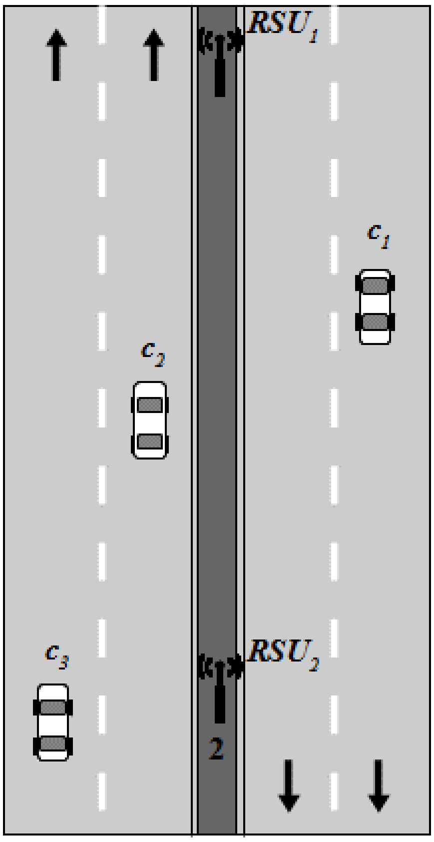

Figure 4-8. Concept of RSU behind the vehicle (RSU_1 is behind c_1). The arrows in the figure denote the direction of travelling.

The global operation relative to RSUs' management (described previously in 4.2.1. and 4. 2.2.) may be seen in Figure 4-9.

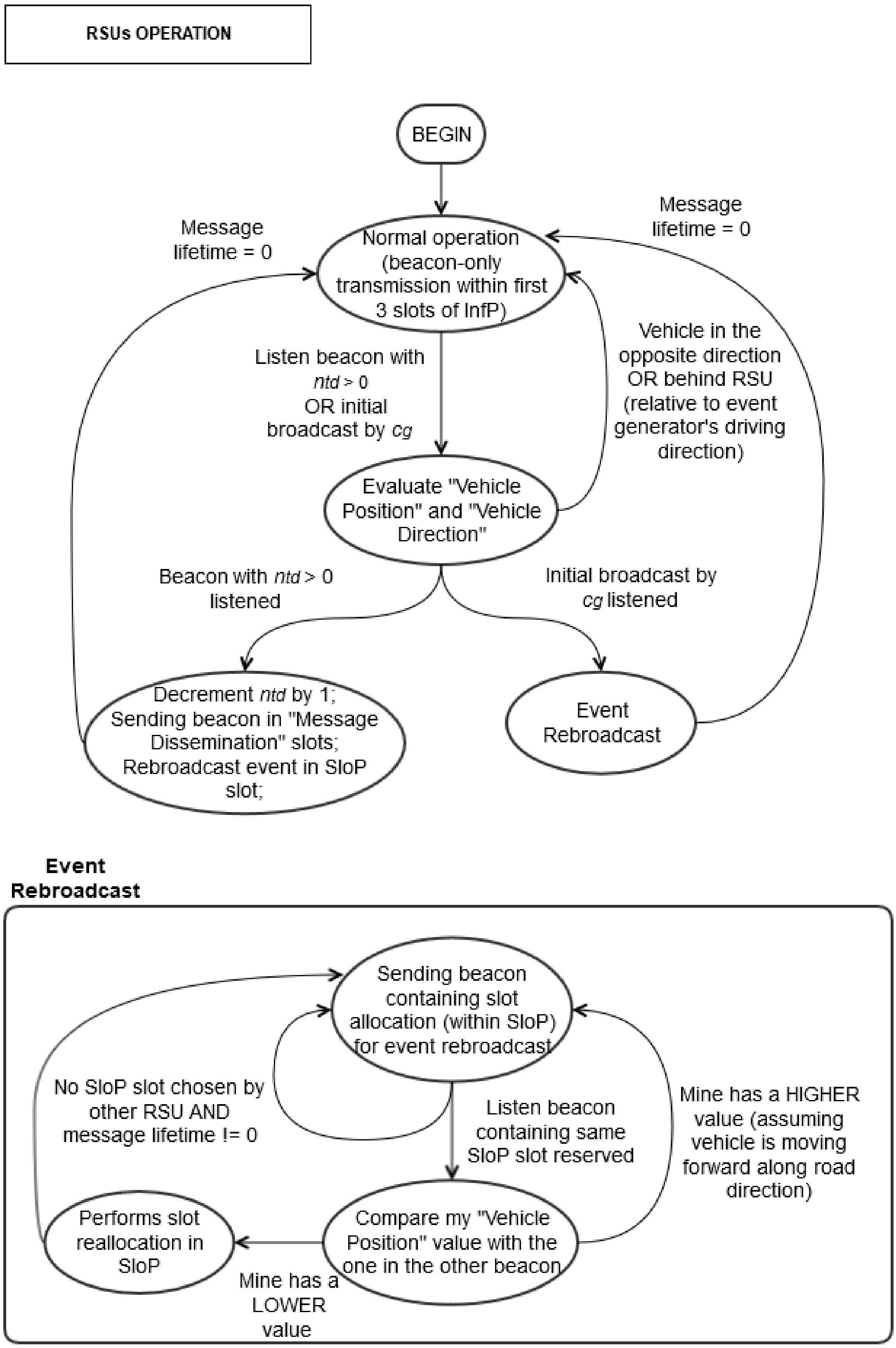

Figure 4-9. RSU operation state machine

4.2.3 Minimizing Transmission Collisions in SloP

Broadcasting status messages, service announcements (WSA), or safety events is done by vehicles within the SloP period. The approach may be using WAVE standard random access. As already stated previously, this will subject transmissions to possible collisions. Other possible approach, aiming to minimize transmission collisions, is performing a deterministic slot choice. Both these approaches are analyzed in terms of collision probability and consequent delay in Section 5.1.2.

In the latter approach, assuming one lane, the slot chosen for a broadcast, $slot_{1lane}$, is based on the vehicle' current position, $x_{Ci}(t)$, and the RSU's position that is behind the vehicle, x_{RSUb}, relative to the direction of travelling, obtained from the beacons heard in InfP. This is given by Eq. (4.3).

$$slot_{1lane} = \left\lfloor SloP(CP) \cdot \frac{\left|x_{C_i}(t) - x_{RSUb}\right|}{d_{cr}} \right\rfloor \tag{4.3}$$

Here $SloP(CP)$ is the number of slots that are available for vehicles within the Slotted Period, and $\lfloor x \rfloor$ represents the rounding of x towards zero to the nearest integer. The vehicle's current position is not the GPS coordinates, but its conversion to road position, as shown in Figure 4-3. Similarly, for the RSU's position.

This approach can be used if it is considered only one lane. However, when considering multiple lanes, as common in highways, some problems may arise. If vehicles are travelling in different lanes "side-by-side", their position will result in the same slot derived ($slot_{1lane}$). For example, in Figure 4-10, vehicles A, C and E will choose slot 0 for message transmission, and vehicles B, D and F will choose slot 3, resulting in a collision if a pair of them (within each "group") have a message to transmit, which is possible. Even when considering the situation seen in Figure 4-11, where vehicles in different lanes are not "side-by-side" (called here "out of phase"), and thus some of the collisions above mentioned would be avoided, it can be seen that due to vehicle spacing the same problem will occur for vehicles B and F. It is assumed here that all vehicles travel at the same speed. This will give the worst-case results. If it was the case that vehicles travelling in different highway lanes have different speeds, a less number of vehicles would exist, since it is likely that vehicles travel faster when driving at the fast lanes (usually the ones at the left when driving is done at right hand side). Thus, with this assumption, the inter-vehicle spacing is the same within all vehicles (for a given traveling velocity), as explained in Section 5.1.

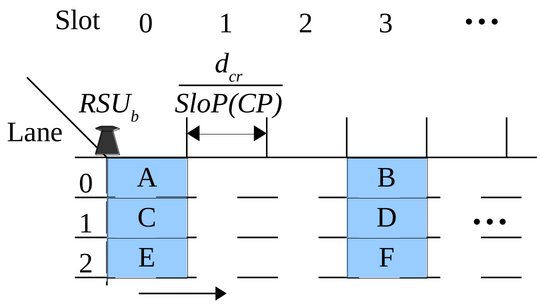

Figure 4-10. Same slot choice due to vehicles in different lanes being "side-by-side".

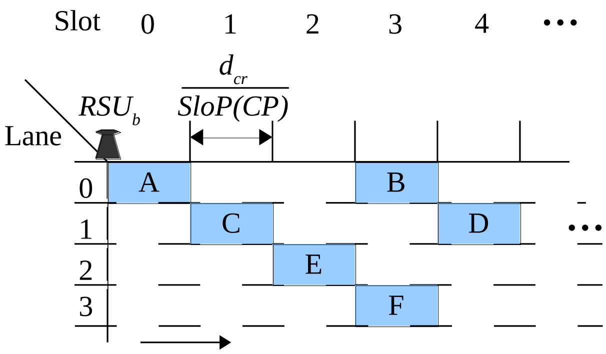

Figure 4-11. Same slot choice (vehicles B and F) in an "out of phase" situation due to vehicle spacing.

With the problem stated above, the method to derive the transmission slot by each vehicle should also take into account the lane number where the vehicle is travelling, $lane_{nr}$, and the number of lanes in each direction, nr_{lanes}. The lane number is the conversion of the GPS coordinates to an integer number, being 0 the most interior lane, and each consecutive following lane obtained by consecutive unity increments (as shown in Figure 4-10).

Considering the case where it is possible to perform slot allocation without collision (fewer or equal number of vehicles than available SloP slots), the goal is to allocate the vehicles within the interior lane (lane 0) to the first $SloP(CP)/nr_{lanes}$ slots, the vehicles in the following lane to the second $SloP(CP)/nr_{lanes}$ slots, and so forth. The total expression used by each vehicle to determine the transmission slot, $slot_{tx}$, is shown in Eq. (4.4).

$$slot_{tx} = \left\lfloor \frac{slot_{1lane} - \left(\langle {slot_{1lane}}/{nr_{lanes}} \rangle \times nr_{lanes}\right)}{nr_{lanes}} + lane_{nr} \cdot \frac{SloP(CP)}{nr_{lanes}} \right\rfloor \quad (4.4)$$

Here, $\langle x \rangle$ represents the fractional part of x and $\lfloor x \rfloor$ represents the rounding of x towards zero to the nearest integer.

To illustrate the process of finding the transmission slot derived by each vehicle by means of Eq. (4.4), an example is given in Table 4-1. In this example, it is considered there are 100 available slots within the slotted period (*SloP(CP)* = 100), the total number of vehicles is also 100, the highway has three lanes in each direction (nr_{lanes} = 3), and the RSU coverage range is 500 meters (d_{cr} = 500 m). The first column gives the vehicle' current position, $x_{Ci}(t)$, in meters, measured in a straight line from the RSU which is behind the vehicle relative to the direction of travelling. The second column defines the lane number where the vehicle is travelling, and the third column gives the slot chosen for a broadcast when only one lane is present, $slot_{1lane}$, derived by means of by Eq. (4.3). Finally, the fourth column gives the transmission slot, $slot_{tx}$, derived by each vehicle by means of Eq. (4.4).

Table 4-1. Example of transmission slot, $slot_{tx}$, derived by vehicles on a highway with multiple lanes by means of Eq. (4.4). Parameters used: *SloP(CP)* = 100; nr_{lanes} = 3; d_{cr} = 500 m.

Vehicle position $x_{Ci}(t)$ **(m)**	**Lane number** $lane_{nr}$	**Derived** $slot_{1lane}$ **(Eq. (4.3))**	**Derived transmission slot** $slot_{tx}$
0	0	0	0
15	0	3	1
480	0	96	32
0	1	0	33
15	1	3	34
480	1	96	65
0	2	0	66
15	2	3	67
480	2	96	98

The example shown in Table 4-1 assumes that the whole number of vehicles are equally spaced through the whole RSU coverage range, and also equally distributed among the lines.

Although this assumption does not represent all the possible scenarios, it can give a good approximation due to vehicle length and inter-vehicle spacing. For example, in Table 4-2 the second column gives the minimum length, in meters, for a different slot be attributed when using Eq. (4.4), and under the assumption of equally distributed vehicles, for different values of *SloP(CP)*.

When analyzing the second column of Table 4-2, since vehicles are usually 4.5 m long, and considering the case of non-congested traffic, where drivers keep some distance to the vehicle ahead, it can be seen that even for the case of fewest slots available (105), the minimum distance is reasonable.

Table 4-2. Minimum inter-vehicle spacing needed for a different transmission slot, $slot_{tx}$, be derived by means of Eq. (4.4). Parameters used: nr_{lanes} = 3; d_{cr} = 500 m.

Slop(CP)	**Minimum length (m)**
105	14.3
155	9.7
206	7.3
245	6.1

The flowchart describing the slot allocation procedure for the initial broadcast is depicted in Figure 4-12.

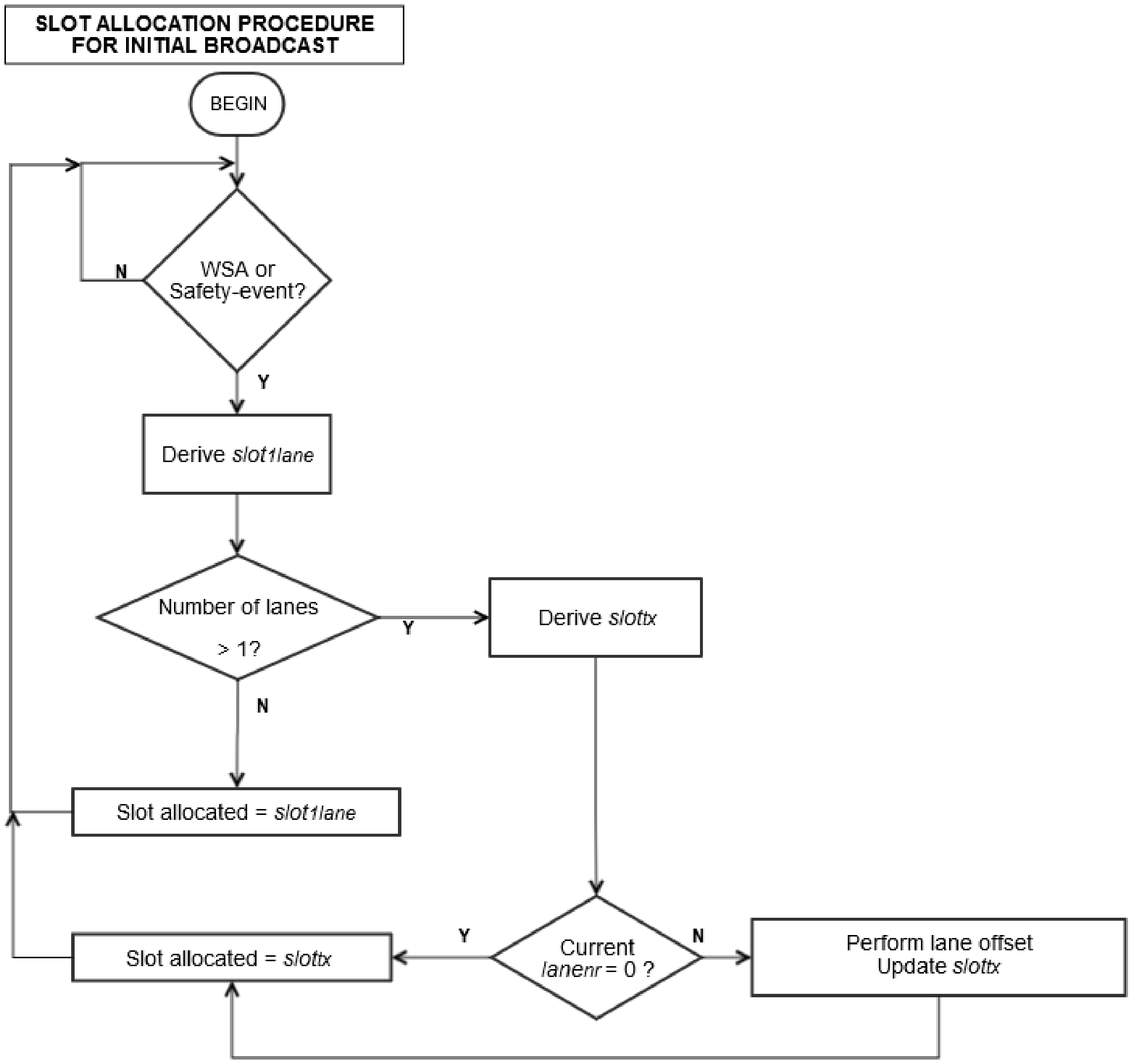

Figure 4-12. Slot allocation procedure for WSMP messages' initial broadcast.

In a situation where all the slots are occupied and a new event generates a safety message with critical transmission delay, the MAC protocol should guarantee that the node's transmission is not blocked (delayed) until a slot is available. Thus, immediate access should be granted. In this sense, since it is not likely that several simultaneous events occur within one CCH interval, a small number of slots can be reserved only for safety events broadcast when all slots are occupied. This situation will be informed by RSUs through their beacons. Alternatively, a possible solution could be to enforce the MAC protocol to allow safety message generation only if it has not listened to other safety event in the immediately previous *x* milliseconds, being *x* a time related with the application. This would prevent

alarm showers to exist, minimizing medium utilization, and consequently a situation where all slots are occupied would be less likely to exist.
Finally, in terms of synchronization, since the devised protocol is "centralized", the RSU can provide the synchronization. However, it is assumed that all units have a GPS module due to the massive use in today's vehicles.

The model devised in sections 4.1 and 4.2 may not be feasible in some cases. First and foremost, full RSU coverage of the highway could not be possible. In addition, highway characteristics, such as tunnels inside which RSUs may not be present, could limit the appropriate dissemination of safety messages if a warning generator vehicle could not communicate with a RSU. In this context, the main goal of the model proposed in the next section is to do the rebroadcast of safety messages only by vehicles.

4.3 An alternative V2V Based Solution

Being V2V communications very promising and much investigated, and taking as base the work done with BRISA – Autoestradas de Portugal SA, a Portuguese highway operator, here it is outlined an alternative solution, where V2V communication plays the major role to accommodate time-critical messages within WAVE, for safety applications in highways.

Ahead, in Chapter 5, it is estimated the number of vehicles in the so-called "distance of interest" (d_E) of a typical scenario, and compared that estimation to the number of available time slots in order to evaluate the model feasibility.

Here, it is considered a highway where RSUs are only present in particular areas, namely all the entry and exit zones, near toll equipment and near possible hazardous areas (dangerous curves, bridges or tunnel entrances). In the highway areas that are not covered by RSUs, vehicles' safety messages can solely rely on V2V communications for being rebroadcasted. The modeled state machine of MAC operation can be seen in Figure 4-13. EP is the Event Period (time interval within CCH interval) and Lifetime relates to the rebroadcast time of an event, as explained later on this section.

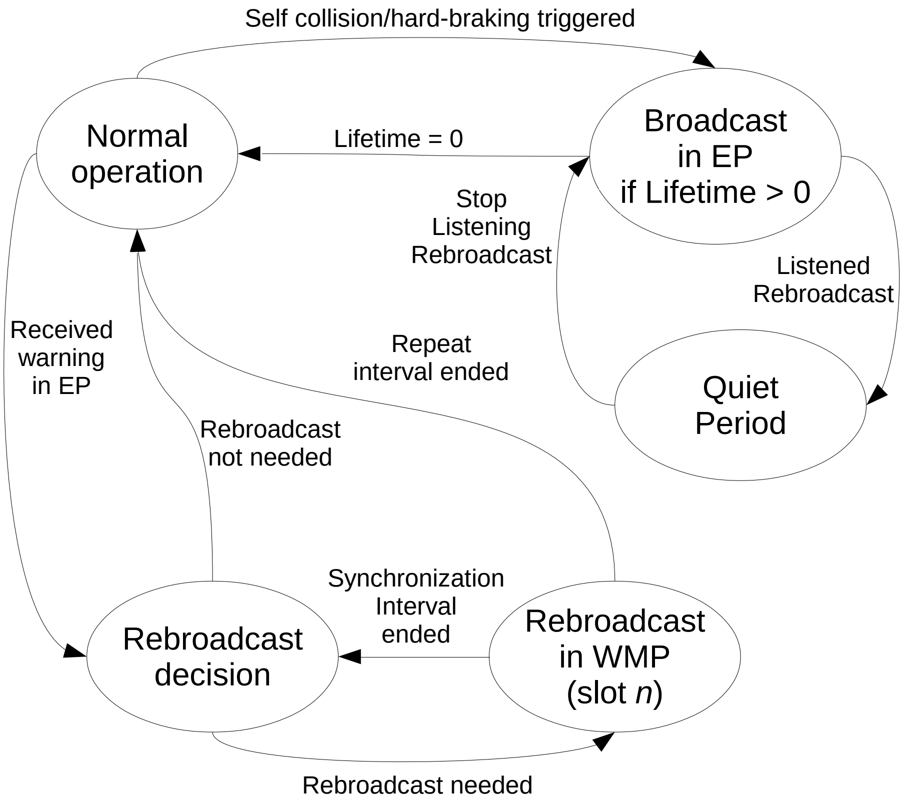

Figure 4-13. MAC state machine (rebroadcast only performed by vehicles)

It is considered that a safety event is associated with a vehicle and this vehicle will be the responsible for disseminating such event. In case of an accident involving multiple cars, several vehicles will consider themselves as being responsible for the same event. The first vehicle gaining access to the medium will broadcast the event and will be the event generator, meaning that the other crashed vehicles will listen to the generator transmission and thus will not start an event on their own. This is further detailed in section 4.3.2 by using a reserved period for event generators.

4.3.1 Model Definition

When the event is recognized, there could be a quantity of vehicles within the distance of interest of the event. This distance of interest depends on the type of event. The model formalization follows.

Consider $E(t_1)$ as a safety relevant event that happened in instant t_1. Below, Eq. (4.5) represents an important group of vehicles.

$$C_{d_E}(t_1) = \{c_g;\ c_0, \cdots, c_n\} \tag{4.5}$$

Here $C_{dE}(t_1)$ is the set of vehicles within the distance of interest of event $E(t_1)$ which includes the generating vehicle c_g and an n+1 (unknown) number of other vehicles, all of which must receive the safety message. To avoid confusing vehicles with velocity we will use the letter c to represent vehicles in the equations, as in c for cars. As already mentioned in Section 4.2, and illustrated in Figure 4-3, we are considering the road in a similar way as used by road authorities.

When a generating vehicle wants to disseminate an event, it will transmit a frame in one of the safety slots reserved for that purpose. Two situations may arise from the transmission of that frame:

1. No vehicle listens to the event generator frame, because there are not any vehicles within the transmission range.
2. Some vehicles listen to the frame.

We could think of a third situation as being the case where there are no free slots. However, and as it is demonstrated and described in Chapter 5, even a worst-case analysis yields sufficient free slots.

Defining an expected instantaneous range (in wireless communications this range fluctuates significantly, but here this is not problematic):

$d_l(t)$ – transmission range, in one direction, at instant t;

$d_l(t_2)$ – transmission range of the message issued by c_g as a reaction to event $E(t_1)$, for $t_2>t_1$ for every t. This is considered constant in any direction, i.e., we are considering circular propagation.

Then, the aforementioned situation 1, where there is not any vehicle within the transmission range of the event generator, leads to Eq. (4.6):

$$C_{dl}(t_2) = \{c_g\} \tag{4.6}$$

where $C_{dl}(t_2)$ is the set that includes the vehicles which are at a linear distance from c_g less than $d_l(t_2)$.

Considering now situation 2 mentioned above, where some vehicles listen to the event generator frame, we have a set of vehicles given by Eq. (4.7):

$$C_{dl}(t_2) = \{c_g; c_0, \cdots, c_k\} \tag{4.7}$$

This set includes the vehicles within the transmission range of c_g, satisfying Eq (4.8):

$$d(c_j) < d_l(t_2), \qquad 0 \leq j \leq k \tag{4.8}$$

where $d(c_j)$ is the distance in a straight line from vehicle j to the generator vehicle.

It should be noted that depending on the distance of interest and the actual vehicles' placement on the road, the set $C_{dE}(t_1)$ may have more, less, or the same number of vehicles than the set $C_{dl}(t_2)$.

It is important to determine a vehicle's position in the road. It can be derived by means of Eq (4.9):

$$x_{ci}(t) = d_{gps}(t_k) + (2f_i - 1)\int_{t_k}^{t} v_i\,dt\,, \qquad t > t_k \tag{4.9}$$

where v_i is vehicle *i* (or car *i*) instantaneous' speed and $d_{gps}(t_k)$ is the position of the vehicle *i* in the road at the last instant where a GPS coordinate has been obtained (e.g. the entrance of a tunnel). The f_i function is used to account the direction which vehicle *i* is travelling, and is given by Eq (4.10):

$$f_i = \begin{cases} 0\ if\ \left(x_{C_i}(t_1) > x_{C_i}(t_2)\right), (t_2 > t_1) \\ 1\ if\ \left(x_{C_i}(t_1) < x_{C_i}(t_2)\right), (t_2 > t_1) \end{cases} \tag{4.10}$$

i.e., if the vehicle is driving back or forward along the road its position goes from D_{rl} to 0 or vice-versa.

The use of Eq. (4.9) allows to determine the vehicle road position in any instant or place, using available GPS information and data available from the vehicle itself, e.g., through the Vehicle On Board Diagnostics II (OBD2) interface (inertial positioning).

One can consider the event relevant for vehicles travelling in both directions, or just consider the generating car driving direction. In a motorway this last scenario is often the relevant one. To find out if vehicle *i* is travelling or not in the same direction as the vehicle that generated the event (c_g), we need to compare f_i and f_g. If they are equal it means that the vehicles are indeed travelling in the same direction.

There is need to restrict this set of vehicles to a distance of interest of the event and driving behind c_g. The vehicles within the distance of interest, d_E, of the event are the ones that have

$$I(c_i) = 1\ if\ \begin{cases} \left(x_{c_i}(t) > (x_{c_g}(t_2) - d_E)\right) \wedge \left(x_{c_i}(t) < x_{c_g}(t_2)\right), f_g = 1 \\ \left(x_{c_i}(t) < (x_{c_g}(t_2) + d_E)\right) \wedge \left(x_{c_i}(t) > x_{c_g}(t_2)\right), f_g = 0 \end{cases} \tag{4.11}$$

$I(c_i) = 0$ otherwise.

Getting back to situation 2, even if $C_{dl}(t_2)$ includes other vehicles than c_g, i.e., there are vehicles within the transmission range, it must be verified if each of those vehicles satisfies Eq. (4.10) and Eq. (4.11) to be considered of interest (i.e., travelling in the same direction, behind the event generator, and within the distance of interest). One of the vehicles within this final subset will rebroadcast the event.

It must be noted that we are ignoring the distance skewing caused by vehicles' mobility due to small differences in relative speed. We recall that event E happened at instant t_1, the frame transmission at instant t_2 and the interest range evaluation at t, where $t > t_2 > t_1$.

In Figure 4-14, it is illustrated a hypothetical scenario reflecting situation 2 mentioned above (take into consideration that scale is not accurate due to print issues, but the figure legends allow accurate and unique interpretation of the scenario). It should be pointed that that the scenario assumes a country where the rule of the road is left-hand traffic. The event generator vehicle is the one marked with a "G" letter. Other vehicles are given a random number, from 0 to 7. The highway has two directions, which are marked with arrows on the leftmost side. The event generator is driving forward (meaning f_g =1). In this particular case, deriving from Eq. (4.7), we would have a subset of vehicles within transmission range of c_g.

$$C_{dl}(t_2) = \{c_g; c_0; c_1; c_2; c_3; c_5; c_6\} \quad (4.12)$$

Also, considering only relevant the vehicles driving in the same direction as the generating car (using Eq. (4.10)), it means that we are now restricted to vehicles c_0, c_1, c_2, and c_3. Taking also into account the distance of interest, and assuming a safety application with d_E = 0.5 km, and also considering only relevant vehicles following c_g (Eq. (4.11)), we would finally get the vehicles c_0 and c_2 considered relevant for rebroadcasting the event.

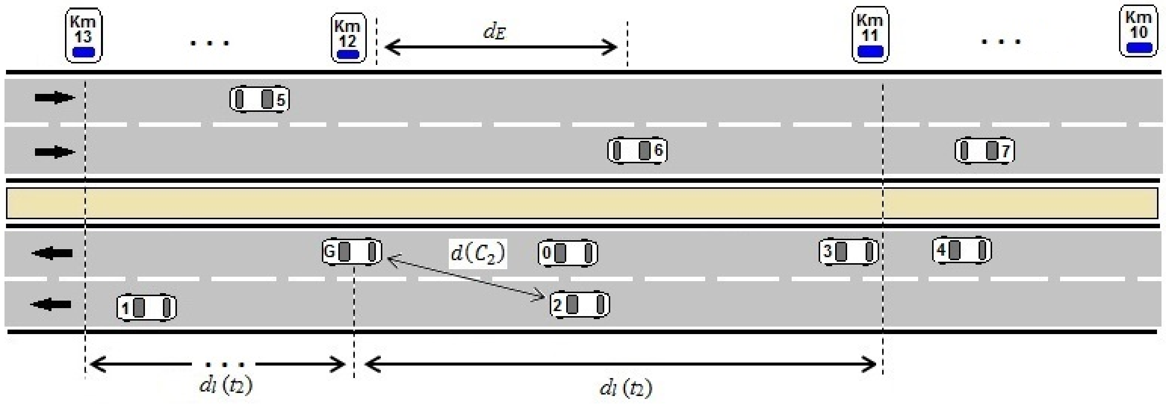

Figure 4-14. Hypothetical scenario for situation 2 (some vehicles listen to the event generator frame).

4.3.2 Event Rebroadcasting Vehicle

Using the aforementioned model, it is important to define some issues. The first should be to decide which vehicle will rebroadcast the safety event, from the set of vehicles chosen as candidates.

As it can be seen in Figure 4-15, the CCH interval is divided into an Event Period (EP) and a Warning Message Period (WMP). The EP is used only by vehicles that generate an event, thus minimizing contention with rebroadcasting vehicles and giving the highest priority to the generator vehicle, c_g. It is possible that simultaneous events can occur. So, the EP is determined after fixating the WMP normal slots needed, and it is composed by a bit-rate dependent number of slots, where each event should be transmitted in one of them.

To minimize contention, the possible simultaneous event generators perform a random choice of a slot within each EP before transmitting the event. The simultaneous generators that do not win medium contention will listen that an event is being broadcasted and will stop trying to broadcast their event. Another approach would be to perform a sort of "position-based" choice of the EP slot to minimize contention (although a reference point should be used).

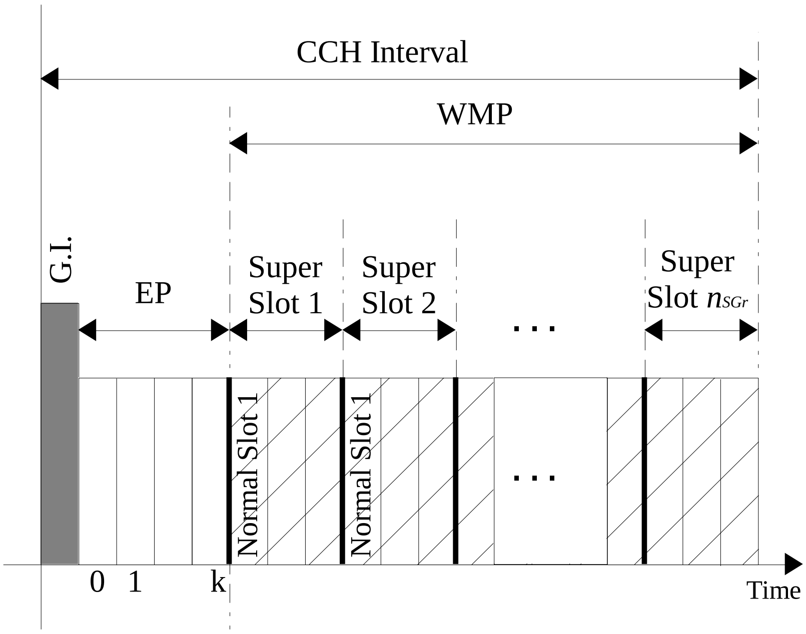

Figure 4-15. TDMA based approach using WAVE's CCH interval.

The WMP works as a Contention Period (CP) and is used only by vehicles that receive a safety frame and are considered relevant to rebroadcast such frame (vehicles c_0 and c_2 in the example of Figure 4-14). It is intended to give different priorities in the slot allocation procedure according to the position of the vehicles, their velocity and also a random number. For this purpose, the WMP is divided as several groups of slots, called Super Slots (SupS). Each SupS has a certain number of Normal Slots (NS). This is shown in Figure 4-15. The priority should be higher for larger distances from the generator vehicle (to reach the largest propagation distance with the minimum necessary broadcasts), which is achieved by the distance related choice of a specific SupS. In a case where the distance results in the same derived SupS of another contending vehicle, a higher priority should be assigned to the vehicle having the lower velocity, since it will stay at a higher distance from the generator vehicle. This is achieved by the velocity related choice of a specific NS within the derived SupS. In case the velocity is also similar to another contending vehicle, leading to the same chosen NS, a random number is used to determine the choice of Sub Slots (SubS) and avoid a transmission collision. This is possible since one NS is sufficient to transmit a safety frame and to have some idle time. Within each NS, there are several SubS related to the time needed to transmit one bit. The number of sub slots should be such that the remaining time in the normal slot is enough to transmit the safety frame and to have an inter-frame space at least equal to SIFS. These measures can minimize significantly the transmission collision probability. The derived super slot, normal slot, and sub slot is obtained by using Eq. (4.13).

So, vehicles receiving a safety frame, that are in the distance of interest behind c_g, (Eq. (4.11)), and moving in the same direction ($f_i = f_g$), should compute the contention period slots, CP_{slots}, in which they will try the rebroadcast in the following CCH Interval. n_{SupS} is the derived super slot number, which is related with vehicle position, n_{NS} is the normal slot number within the chosen super slot, which is related with vehicle velocity, and n_{SubS} is the sub slot number within the chosen normal slot, which is obtained by using a random number and is used to avoid a transmission collision between vehicles having similar positions and velocities.

$$CP_{slots}\begin{pmatrix} n_{SupS}, \\ n_{NS}, \\ n_{SubS} \end{pmatrix} = \begin{pmatrix} \left(n_{SGr} - \left\lfloor \frac{n_{SGr} \cdot \left|x_{c_i}(t) - x_{c_g}(t_2)\right|}{d_l(t_2)} \right\rfloor\right), \\ \left(\left\lceil \frac{vel_i - vel_{min}}{gap_{vel}} \right\rceil\right), \\ (random(0,1) \cdot k_{SubS}) \end{pmatrix} \tag{4.13}$$

Here n_{SGr} is the number of super slot groups, $x_{ci}(t)$ is the vehicle's current position, relative to the position of the generator vehicle at the time of event generation, $x_{cg}(t_2)$, vel_i is the vehicle's i velocity, vel_{min} is the minimum velocity defined for a vehicle, k_{SubS} is the number of sub slots, and gap_{vel} is given by Eq. (4.14):

$$gap_{vel} = \frac{vel_{max} - vel_{min}}{k_{NS}} \tag{4.14}$$

Here vel_{max} is the maximum velocity defined for a vehicle and k_{NS} is the number of normal slots within a super slot.

An example of the derived contention period Super Slot (n_{SupS}) and Normal Slot (n_{NS}) number, with application of Eq. (4.13), according to the vehicle's current position, $x_{ci}(t)$, and vehicle's current velocity, vel_i, is given in Table 4-3. This example assumes there are ten super slot groups (n_{SGr} = 10), each one composed by three normal slots (k_{NS} = 3). The minimum and maximum velocities defined for a vehicle are 40 km/h and 220 km/h, respectively, and the transmission range of the message issued by c_g is 200 meters ($d_l(t_2)$ = 200).

Table 4-3. Contention period slots, CP_{slots}, derived by means of Eq. (4.13). Parameters used: n_{SGr} = 10; k_{NS} = 3; vel_{min} = 40 km/h; vel_{max} = 220 km/h.

Vehicle position $x_{Ci}(t)$ (m)	**Vehicle velocity vel_i (km/h)**	**Derived Super Slot, n_{SupS}**	**Derived Normal Slot, n_{NS}**
0	45	10	1
0	105	10	2
0	170	10	3
100	45	5	1
100	105	5	2
100	170	5	3
199	45	1	1
199	105	1	2
199	170	1	3

It should be noticed that, after receiving a safety message, and earning the right to rebroadcast through slot allocation procedure, the rebroadcasting vehicle will act as a new generator vehicle for the vehicles behind it and the process repeats for such vehicles.

Another interesting issue is whether c_g should continue to broadcast the event. Here it is considered appropriate, in sake of medium resources utilization, that when a generating vehicle listens to a rebroadcast, it should stop trying to broadcast itself the safety message. If it never detects a rebroadcast or, after some time, stops listening to the rebroadcast, the generator vehicle starts repeating the broadcast if the message's lifetime (t_{lf}) is not zero.

Consequently, it can be questioned what lifetime should the event have, i.e., how long must we continue to rebroadcast the event? Also, at what distance must the event be propagated?

Both questions cannot be answered in an absolute manner. This is application dependent. For example, an EEBL message will surely have a shorter lifetime than an accident warning. The same applies to the distance. For example, an accident can cause a traffic jam for various kilometers, while in the case of a sudden braking it is not needed to warn vehicles that are too far away. The message's lifetime should be enough to ensure that at least one vehicle will receive the message, i.e., it should account for an initial absence of vehicles within the transmission range, or connectivity loss due to sudden deceleration.

In order to perform an evaluation for different scenarios (done below in Chapter 5), it is useful to determine how many vehicles are in the distance of interest (n_{dE}) of a possible event generator (c_g). This is shown in Eq. (4.15).

$$n_{d_E} = \frac{d_E}{(c_{length} + c_{spacing})} \times n_{lanes} \tag{4.15}$$

Here n_{lanes} is the number of highway lanes in each direction, c_{length} is the vehicle average length, and $c_{spacing}$ is the inter-vehicle separation gap.

In conclusion, this chapter built upon the assumption that V2V technology will gradually be introduced in new vehicles and will take some time for safety applications be fully functional on the road. With this in mind, a TDMA infrastructural solution was devised, where RSUs take part in the network as a special element, in order to take advantage of the characteristics of an infrastructure-based MAC protocol. The second part of the chapter focused on providing an alternative solution, using only V2V based communications to accommodate time-critical messages within WAVE, for safety applications in highways. This is for cases where full RSU coverage of the highway could not be possible, or the highway characteristics, such as tunnels, could limit the appropriate dissemination of safety messages. Also, the promising potential of V2V communications as well as the almost certainty that those will be present in a near future on roads, was an aspect taken into consideration.

When dealing with safety critical applications, where a safety event that is generated by a vehicle needs to be delivered timely, the study of the MAC end-to-end delay performance metric is of utmost importance. This allows one to assess the suitability of a devised MAC protocol for such application. The following chapter covers this aspects.

CHAPTER 5

THEORETICAL VALIDATION

Summary

This chapter devises the delay model and performs analytical calculations in order to assess the suitability of the proposed MAC schemes.

5.1 MAC Protocol Performance Evaluation Model

Since practical and real world validation of VANETs' protocols is complex and expensive, due to the high number of vehicles involved as well as the distributed scenario needed, theoretical validation, which will be made in this section, assumes a character of great importance.

Most works studying the theoretical performance of the IEEE 802.11 MAC DCF using CSMA/CA protocol provide mathematical models confined to special cases such as single hop networks operating on a saturated medium assumption. This means that every node in the network has a packet to send at any time. However, the saturated model restricts the end-to-end delay performance full study since it does not consider the impact of the MAC layer queue.

The end-to-end delay analysis of IEEE 802.11p/P1609.4 MAC protocol, including the specificity of control channel (CCH) and service channel (SCH) usage, under any load condition, has scarce research till date. In this part of the thesis it is devised the end-to-end delay model of a specific WAVE MAC protocol, relying in V2V and V2I single-hop communication for timely delivery of safety messages. The goal is to evaluate the delivery latency achieved after the occurrence of a safety event. It should be noted that the MAC delivery latency (end-to-end delay) is the sum of the medium access delay along with the queuing delay.

It is important to know the maximum number of vehicles at the transmission range of a specific RSU. Using Eq. (4.15), and switching in the numerator the distance of interest for the transmission range of a RSU at instant *t* (i.e., d_E for d_l (*t*)), and also using the modifications made in (MEIRELES, FONSECA, 2011) to account for the existence of trucks at a certain percentage, Tr_{pct}, it is possible to obtain the maximum number of vehicles at the range (radius) of a specific RSU, n_{c_max}, by using Eq. (5.1):

$$n_{c\_max} = \frac{d_l(t)}{\left[\left(c_{length} \times \left(1 - Tr_{pct}\right) + Tr_{length} \times Tr_{pct}\right) + S(V)\right]} \times n_{lanes} \qquad (5.1)$$

Here c_{length} is the vehicle's length, Tr_{length} is the trucks' length, and $S(V)$ is the inter-vehicle spacing, which depends on the vehicular mobility model used. Considering the intelligent driver model (IDM) (TREIBER, HENNECKE, HELBING, 2000) for the equilibrium traffic condition, where drivers tend to keep a velocity-dependent equilibrium gap to the front vehicle, the mean equilibrium gap between two adjacent cars, *S*, is described by (TREIBER, HENNECKE, HELBING, 2000) as shown in Eq (5.2):

$$S(V) = (S_0 + V \cdot \tau)\left[1 - \left(\frac{V}{V_0}\right)^{\delta}\right]^{-\frac{1}{2}} \tag{5.2}$$

Here S_0 is the bumper-to-bumper space kept in standing traffic, τ is the safe time headway (1.8 seconds is used), V_0 is the desired velocity when there is no leading vehicle, and δ is the acceleration exponent. The coefficient δ influences the transition region between the free and congested regimes, with lower values being used for smoother transition.

It is assumed that all vehicles travel at the same speed. This will give the worst-case results. If it was the case that vehicles travelling in different highway lanes have different speeds, a smaller number of vehicles would exist, since it is likely that vehicles travel faster when driving at the fast lanes (usually the ones at the left when driving is done at right hand side). Thus, with this assumption, the inter-vehicle spacing is the same within all vehicles (for a given traveling velocity).

Regarding the instant where the safety event takes place within the synchronization intervals, various scenarios are possible. Here, two are considered, the so-called worst-case and best-case scenarios detailed further ahead. In both, the Infrastructure Period (InfP) has allocated five slots, as explained in Section 4.2. Recalling briefly, this is because the coverage area of a RSU is overlapped with the adjacent RSU. Therefore, considering it is important each RSU listens to the beacons of two adjacent RSUs, three slots are sufficient, with the other two being reserved for the purpose of message dissemination.

The InfP duration depends consequently on the number of slots and the duration of each slot. Since each slot is used to transmit beacon frames (Figure 4-7), and their payload size is 225 bits, the duration of each slot is easily determined for each bit rate. Having the InfP duration defined, the Slotted Period (SloP) duration is the rest of the CCH interval. The longer the safety message is, the fewer the slots within SloP will be available. The message duration at a certain bit rate, plus the minimum AIFS for an OBU (which is, according to the standard, the time correspondent to AIFSN = 2, Figure 3-2), plus the maximum backoff window duration, will match the duration of one slot. Dividing the SloP duration for this will give the number of total slots available within SloP period. If the six slots reserved for RSUs' rebroadcast are subtracted, it is possible to know how many slots are available for vehicles, willing to broadcast initially a safety event or other high priority messages. The number of slots for both is given in Eq. (5.3):

$$\begin{cases} InfP(s) = 5 \times (beacon_{duration} + AIFS + aSlotTime) \\ SloP(CP) = \dfrac{CCH_{int} - GI - IP}{(message + SIFS + 2 \cdot aSlotTime + CW_{max} \cdot aSlotTime)} - 6 \end{cases} \quad (5.3)$$

where CCH_{int} is the duration of the CCH interval, *GI* is the guard interval, *InfP(s)* is the Infrastructure Period duration in seconds, CW_{max} is used for the maximum backoff possible (and has a value of 7 for the CCH and for the highest AC messages), and *SloP*(*CP*) is the number of slots within the Slotted Period that are available for vehicles.

5.1.1 Worst-Case / Best-Case Scenarios Regarding the Safety Event Instant

Regarding the slot used within the SloP by the event generator, since it is unknown, even in the case of using an approach, to the choice of the transmission slot, that aims to minimize collisions, as detailed in Section 4.2.3., it will be assumed the middle slot of the total number of slots existent within the SloP period. As a worst-case scenario it is considered that the safety event occurs in the beginning of a CCH interval, the event generator fails to access the medium in the corresponding SloP, and the safety event (e.g., hard-braking) is initially broadcasted in the following CCH interval, within SloP. Therefore, the medium access delay for the worst-case, t_{m_wc}, is given by Eq. (5.4):

$$t_{m\_wc} = CCH_{int} + SCH_{int} + GI + InfP + \frac{1}{2}SloP \quad (5.4)$$

Here SCH_{int} is the duration of the SCH interval, *SloP* is the duration of the Slotted Period, and *InfP* is the duration of the Infrastructure Period.

The best-case scenario is assumed to be the one where the safety event occurs in the beginning of a CCH interval, and the event generator manages to broadcast the corresponding safety message within the SloP of the current CCH interval. Therefore, the medium access delay for the best-case, t_{m_bc}, is given in Eq. (5.5):

$$t_{m\_bc} = GI + InfP + \frac{1}{2}SloP \tag{5.5}$$

In Figure 5-1 it is illustrated the time instant where the safety event occurs (red triangle), and the instant of the respective broadcast in the best-case (green circle) and worst-case (green ring) scenarios.

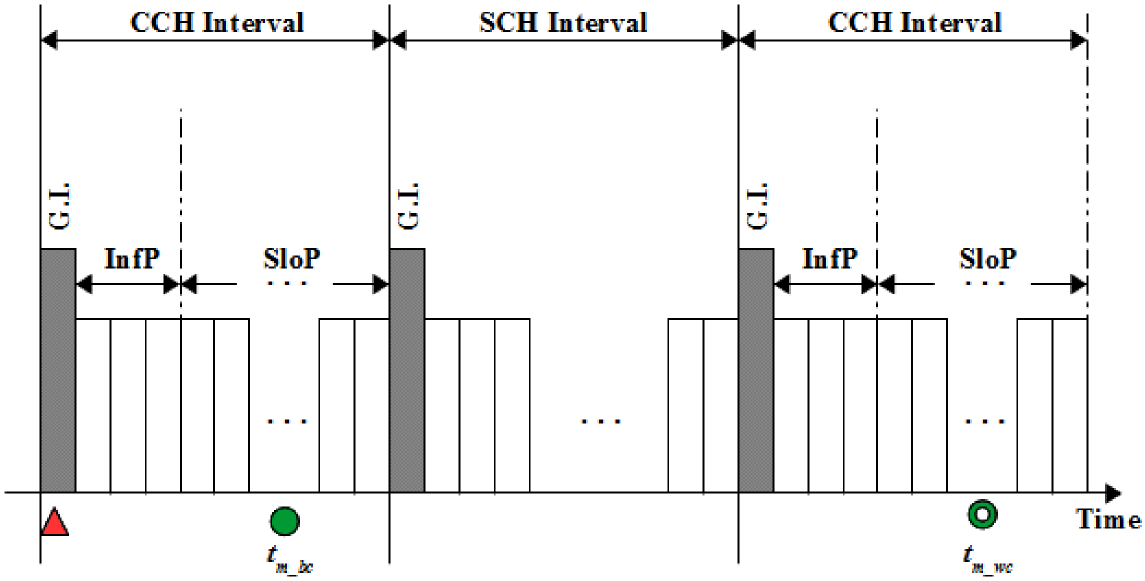

Figure 5-1. Best-case (green circle) and worst-case (green ring) scenarios for medium access delay after the occurrence of a safety event (red triangle).

5.1.2 Medium Access Delay

The medium access delay, t_m, is defined as the interval from the time a packet is elected for transmission by the MAC layer (it is at the head of the queue) until the packet is successfully received by the recipient. It should be noted that although the propagation delay is not explicitly shown in the following equations that contribute to the end-to-end delay, it is already taken into account within the time of a slot (D2 in Figure 3-2). In addition, when using OFDM of WAVE, the propagation time is much smaller than one microsecond, and will have a negligible effect on the following calculations.

Since after the initial broadcast, contention is avoided and message dissemination is done by RSUs, the medium access delay is mainly due to the RSUs' scheduling time and the

WAVE synchronization intervals organization. We will assume that RSUs' scheduling is performed within the current CCH interval which means the event is surely disseminated in the following CCH intervals, after the initial broadcast. As defined in the standard, safety messages should only be transmitted within the CCH interval, since all vehicles listen to it. In this sense, and considering single radio devices are used, an alternating access to CCH and SCH is assumed here (Figure 2-9). The delay estimated is for the initial broadcast. Due to protocol design, and CCH and SCH usage, the following messages will always have a delay equal to a synchronization interval (100ms).

Having defined the worst and best-case scenarios, the average medium access delay, t_m, can be derived from both (Eq. (5.6)). Comparing them, the main difference is that for the worst-case scenario the safety event generator cannot get access to the communication medium in the first SloP, in order to perform the initial broadcast. This situation relates to the so-called final collision probability p_{collf}. This is the probability of at least two OBUs having messages to transmit and both choosing the same SloP slot (Eq. (5.7)). For the worst-case, it is also assumed that the safety event is successfully broadcasted only in the second attempt. This assumption is based on several aspects. Note that a safety message belongs to the highest priority class and wins contention over other non-safety messages. Also, it is not likely that a lot of simultaneous (within the same CCH time interval) safety events occur. Finally, a scheme reducing the randomness, and consequently the collision probability, may be used, as it was detailed in Section 4.2.3.

$$t_m = t_{m\_bc} \cdot \left(1 - p_{collf}\right) + t_{m\_wc} \cdot p_{collf} \tag{5.6}$$

$$p_{collf} = p_{coll} \cap p_{same\_slot} \tag{5.7}$$

The collision probability, p_{coll}, is the probability that at least two OBUs transmit a packet, and it is given in Eq. (5.8). Thus, it depends on the transmission probability, p_{tx}, and the number of stations, N, from the highest priority AC (VASSIS, KORMENTZAS, 2005). The author in (BIANCHI, 2000) introduced an approximation based on the assumption that each packet has constant and independent collision probability, regardless of the number of retransmission already suffered. This assumption will also be used here. Also, it is assumed there are only stations having highest priority messages, thus all contending for medium access.

$$p_{coll} = 1 - (1 - p_{tx})^{N-1} \tag{5.8}$$

The transmission probability is the probability that a station has a packet to send, and its backoff timer expires given that it has a packet to send. This is given in Eq. (5.9). The probability that it has a packet to transmit is equal to the utilization factor ρ (the percentage of time in which there is a packet in the server of an M/G/1 queue). The probability that the backoff counter expires, given that there is a packet to transmit, is $1/W$ (VASSIS, KORMENTZAS, 2005), where W is the backoff window size. The backoff is uniformly distributed over [1, CW_{min}+1] in the first transmission attempt.

$$p_{tx} = \rho \cdot \frac{1}{W} = \frac{\lambda \cdot t_m}{W} \tag{5.9}$$

The probability that at least two OBUs choose a same SloP slot for transmission, p_{same_slot}, can be derived assuming two distinct situations. In the first the event generator chooses randomly the slot within SloP to perform the corresponding broadcast. In the second, the event generator choses its slot based on its current position and the closest RSU's position.

5.1.2.1 Random Choice of SloP Slot for Generator Broadcast

In this situation, the slot chosen for the initial broadcast is picked randomly from the total number of slots, *SloP(CP)*, obtained from Eq (5.3).

The probability of all vehicles choosing a different slot randomly, p_{free_r}, depends on the total number of slots available, and the number of vehicles (Eq. (5.1)), and could be used to determine the probability that at least two vehicles choose randomly a same slot for transmission, $p_{same\_slot\_r}$. This is given by the set in Eq. (5.10).

$$\begin{cases} p_{free\_r} = \begin{cases} \dfrac{Slop(CP)!}{SloP(CP)^{n_{c\_max}} \times (Slop(CP) - n_{C\_max})!}, Slop(CP) \geq n_{c\_max} \\ 0\,, SloP(CP) < n_{c\_max} \end{cases} \\ p_{same\_slot\_r} = 1 - p_{free\_r} \end{cases} \tag{5.10}$$

It should be noted that the probability p_{free_r} is calculated in the cases where there are the same or more slots available than there are vehicles. In the other cases the probability is zero.

5.1.2.2 Position-based Choice of SloP Slot

If the number of vehicles given by Eq. (5.1), n_{c_max}, exceeds the number of SloP slots available for vehicles, $SloP(CP)$, it is for certain that at least two vehicles will choose the same slot. Thus, the division between the two gives the number of vehicles within one slot, $n_{c\_one\_slot}$, and is shown in Eq. (5.11):

$$n_{c\_one\_slot} = \frac{n_{c\_max}}{SloP(CP)} \tag{5.11}$$

The probability that at least two vehicles choose the same slot, $p_{same\_slot\_d}$, is given by Eq. (5.12).

$$p_{same\_slot\_d} = \begin{cases} 0 \text{ , } n_{c\_one\_slot} \leq 1 \\ 1 \text{ , } n_{c\_one\_slot} > 1 \end{cases} \tag{5.12}$$

5.1.3 Queuing Delay

When using EDCA virtual collisions may occur, which means there are packets to transmit from two different priority queues (internal contention). The collision management mechanism imposes that the queue with highest priority will win the right to try to access the medium. Since safety messages are categorized as highest priority messages, it means that even if there are currently other lower priority messages in their queues, a message correspondent to a safety event will be the one competing for access to the medium (wins internal contention). Therefore the queuing delay is only due to the other highest priority messages present on that same queue.

Under finite load conditions the utilization factor of each station is $\rho < 1$ ($\rho = \lambda / \mu$, where λ is the expected packet generation rate and μ is the corresponding expected packet service rate). In order to simplify the analysis, as done in (BIANCHI, 2000) and (VASSIS, KORMENTZAS, 2005), it is assumed that the generated traffic can be described with a Poisson process. Therefore, we can model each station with an M/G/1 queue with a birth rate of λ packets/second. The expected number of packets waiting in the highest priority transmitter queue, Q, is given from the Pollaczek-Khinchin mean-value formula (KLEINROCK, 1975):

$$Q = \rho^2 \frac{1 + C_{bi}^2}{2(1 - \rho)} \tag{5.13}$$

Here C_{bi} is the coefficient of variation of the medium access delay and is equal to σ_{tm}/t_m, where σ_{tm} is the standard deviation of the medium access delay. The utilization factor may be rewritten as $\rho = \lambda \cdot t_m$ since the service rate is $1/t_m$. Using Little's theorem, the queuing delay, t_q, can be obtained by dividing Eq. (5.13) by λ.

5.2 Results

5.2.1 I-TDMA Solution

The delay model explained previously on Section 5.1. will now be used to estimate the MAC protocol end-to-end delay.

5.2.1.1 Constant Parameters

Since the proposed solution is based on time slots, the duration of each slot during SloP is defined as the time needed to transmit a safety message, despite it could be used to transmit other periodic data, such as beacons or WSAs. Aiming for the worst-case, the longer the size of the safety message, fewer slots will be available within SloP. Therefore, it is considered the Pre-crash Sensing for Collision Mitigation since it has 435 bits of payload (US DoT, 2005), and is the longest safety message that a vehicle can transmit. In 802.11p the channel bandwidth is halved in order to keep abreast the requirements of VANETs, resulting in a 10 MHz bandwidth instead of 20MHz as in 802.11a (ABDELDIME, WU, 2014). The consequent values of the related parameters are: a Short Inter-frame Spacing (SIFS) of 32 microseconds and a slot time of 13 microseconds. The initial Guard Interval (G.I.) in every CCH/SCH interval is 4 milliseconds, being the duration of the CCH/SCH interval 50 milliseconds each.

The backoff window, W, is uniformly distributed over [1, CW_{min}+1] in the first transmission attempt. The parameter CW_{min} is defined in the standard, and for the case of safety messages (highest access category, AC = Voice) it has a value of 3. Aiming for worst-case analysis, where higher backoff waiting time will also lead to higher medium access delay, and since this could be set by software, it will be used a constant value of W equal to 4. Please note that a constant value also means higher collision probability.

The transmission range of a RSU, $d_l(t)$, is a function of the transmission power used. Values from 200 meters to one kilometer are seen in the literature. Since this value also depends on the physical conditions and obstacles, it is assumed here to be 500 m.

Relatively to the truck percentage being considered the authors (ZHU, 2004) show that is less than 15% in about 80% of freeway. The two most common situations occur at 5% and at 13% (Figure 5-2). Since the lower the percentage is, the higher the number of vehicles within the coverage area is, and aiming for the worst-case analysis, it is considered here a truck percentage, Tr_{pct}, equal to 8%. On a side note about considering a higher percentage, e.g., 8%, the difference between those two percentages (5% and 8%) affects the number of vehicles only at lower speeds. For velocities higher than 30 km/h the number of vehicles remains the same. This is an effect of inter-vehicle spacing.

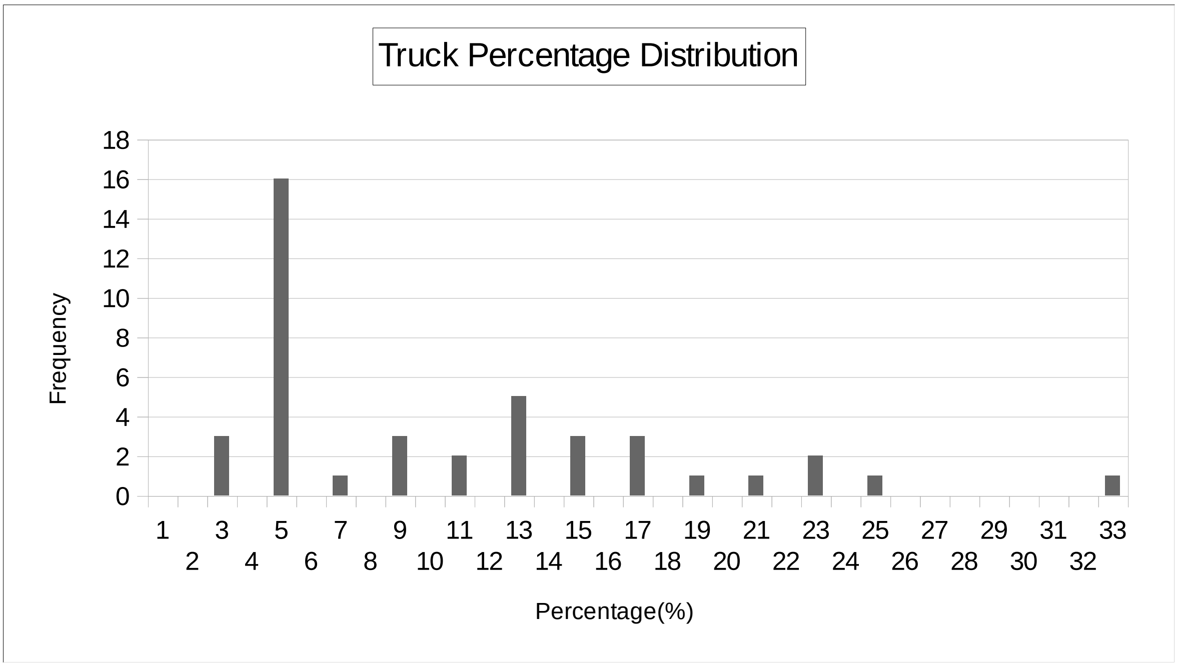

Figure 5-2. Truck percentage distributions (ZHU, 2004)

The constant parameters used in the intelligent driver model for inter-vehicle spacing are S_0 (bumper-to-bumper space kept in standing traffic), τ (safe time headway), V_0 (desired velocity when there is no leading vehicle), and δ (acceleration exponent).

Table 5-1. Constant parameters used in all considered sets (10MHz channel spacing).

Constant Parameters Used (10MHz channel spacing)	
c_{length}	4,5 m
T_{length}	10 m
$d_l(t)$	500 m
Tr_{pct}	8%
n_{RSUs}	3
CCH_{int}	50 ms
SCH_{int}	50 ms
GI	4 ms
$SIFS$	32 μs
$aSlotTime$	13 μs
$AIFSN_{RSU}$	1
$AIFSN_{Vehicle}$	2
S_0	2 m
τ	1,8 s
V_0	125 km/h
δ	4

Using Eq. (5.3) the number of slots contained within the SloP period can be determined for each of the bit rates used, as seen in Figure 5-3.

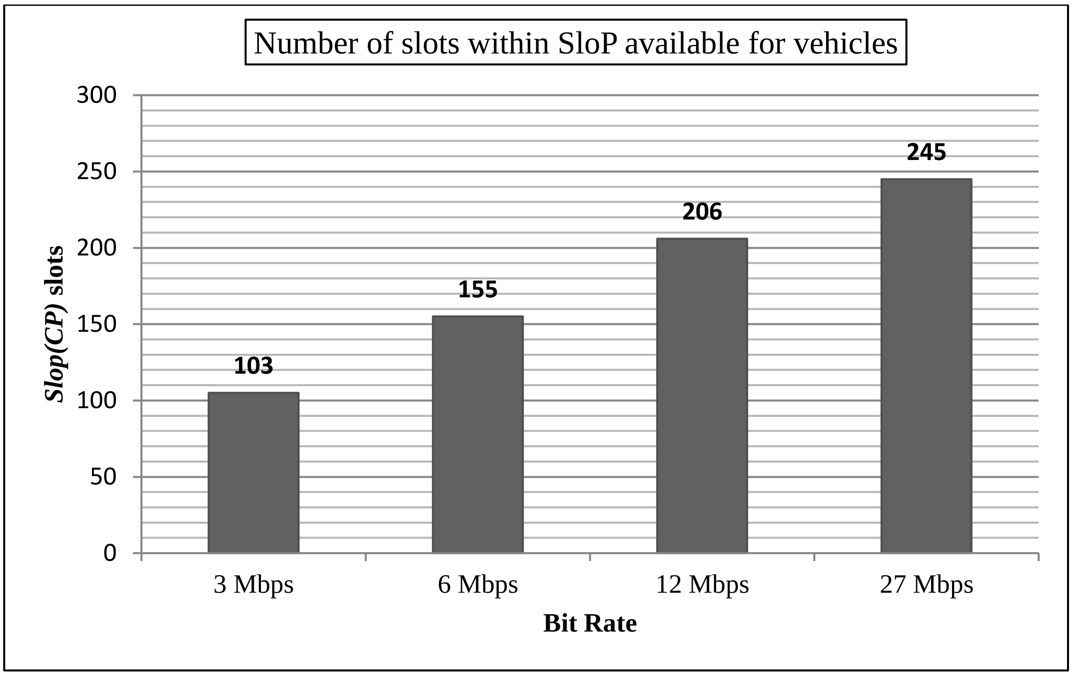

Figure 5-3. Number of slots contained in SloP Period vs. Bit Rate

As said before, the number of slots is a function of the message duration (CFCW considered as a worst-case) and also the RSUs' beacons duration. This number will keep approximately constant for beacons as long as 450 bits, losing only one slot in the three lower bit rates.

As expected, as the bit rate increases, the message slot duration needed to transmit the safety message decreases, thus leading to an increased number of slots available for safety-related messages (periodic or event-driven).

5.2.1.2 Medium Access Delay – Set 1: Number of lanes = 3, 80% of $S(V)$, λ = 5

Regarding the number of lanes of the highway, normally the traffic is low and the speed is not too fast when considering two lanes. At three or more lanes the speed is comparatively faster (WANG, 2008). Thus, here it will be considered three lanes in each direction of the highway.

Aiming for the worst-case analysis, and using Eq. (5.2), it will be used 80% of $S(V)$, representing a less cautious driving, and in some cases maybe a better approximation to reality since drivers usually tend to keep the space between vehicles less than the desirable. It is less likely that a safety event is generated at lower speeds than it is at higher speeds. Moreover, at lower velocities the risk to physical integrity of human beings is reduced. The number of vehicles n_{c_max} is the maximum allowed number within a coverage range considering a specific velocity and its correspondent inter vehicle spacing. This could be related as a peak hour. However, it is possible that fewer vehicles are present at the road within the same coverage range.

5.2.1.2.1 Inter-Vehicle Spacing, $S(V)$, and Number of Vehicles

So, using Eq. (5.2), and multiplying $S(V)$ by 80%, the inter-vehicle spacing may be obtained as a function of vehicles' speed. In Figure 5-4 it is plotted from 5 km/h to 120 km/h. In most European and U.S. highways the speed limit is equal or less than 120 km/h (EU SPEED LIMITS, 2014)(US SPEED LIMITS, 2014). Despite some exceptions exist, higher speeds will lead to an even larger inter-vehicle spacing, thus even less vehicles within the coverage area, so it is not considered here.

From the relation between speed and inter-vehicle spacing in Figure 5-4 it is noted that, when speed exceeds approximately 100 km/h the curve approaches more an exponential than a linear function. This notes, as stated in the traffic model used, that drivers tend to keep a velocity-dependent equilibrium gap to the front vehicle.

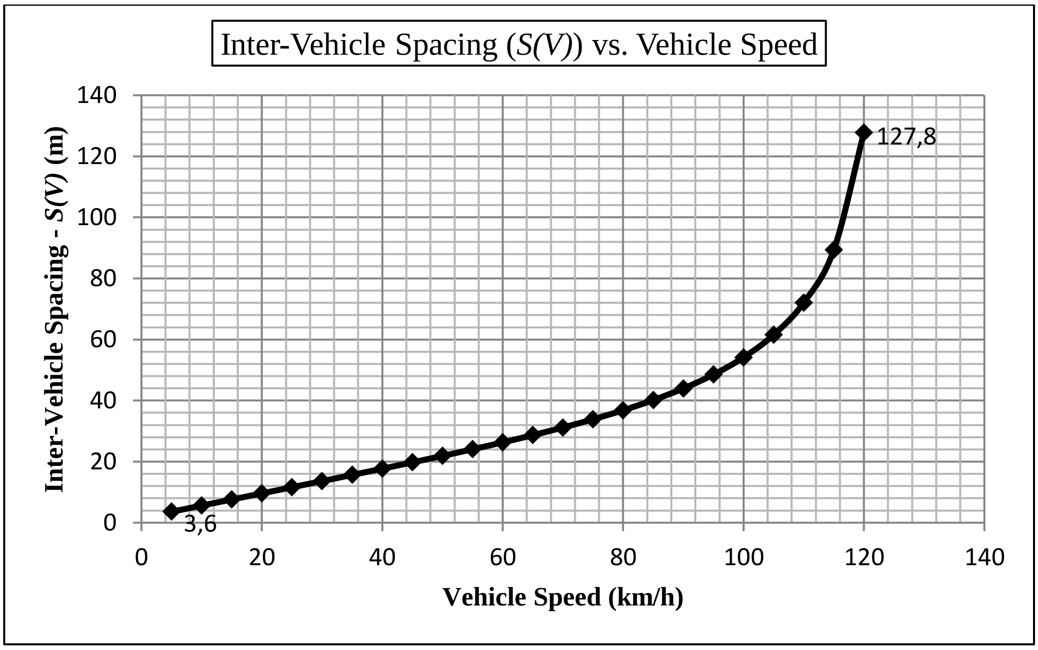

Figure 5-4. Inter-Vehicle Spacing, $S(V)$, vs. Vehicle Speed

Having the inter-vehicle spacing well defined for each velocity, the number of vehicles can be obtained by Eq. (5.1). In Figure 5-5 it can be seen the number of vehicles existent at the range of a RSU when using the parameters considered in Table 5-1. This follows the shape of a decreasing exponential. So, the higher the inter-vehicle spacing is (due to a higher vehicle speed), the lower the number of vehicles that are within the coverage range of a RSU.

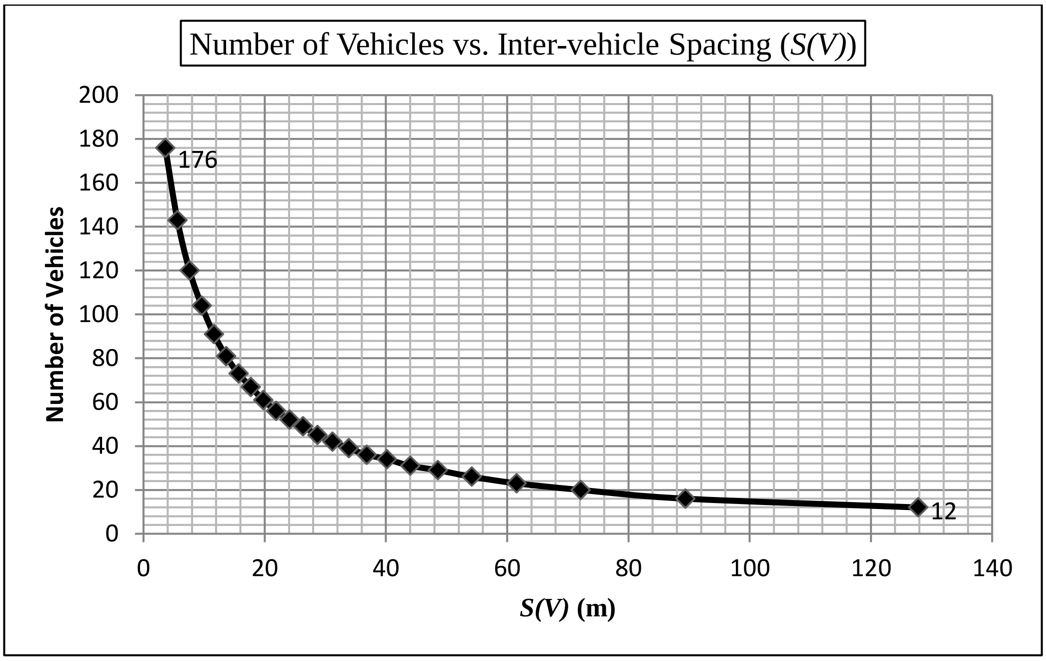

Figure 5-5. Number of Vehicles vs. Inter-Vehicle Spacing, *S*(*V*)

5.2.1.2.2 Collision Probability, p_{collf}

Since the medium access delay is related to the probability of at least two OBUs having messages to transmit and both choosing the same SloP slot (collision probability, p_{collf}), it is interesting to represent graphically its value as a function of vehicles' speed.

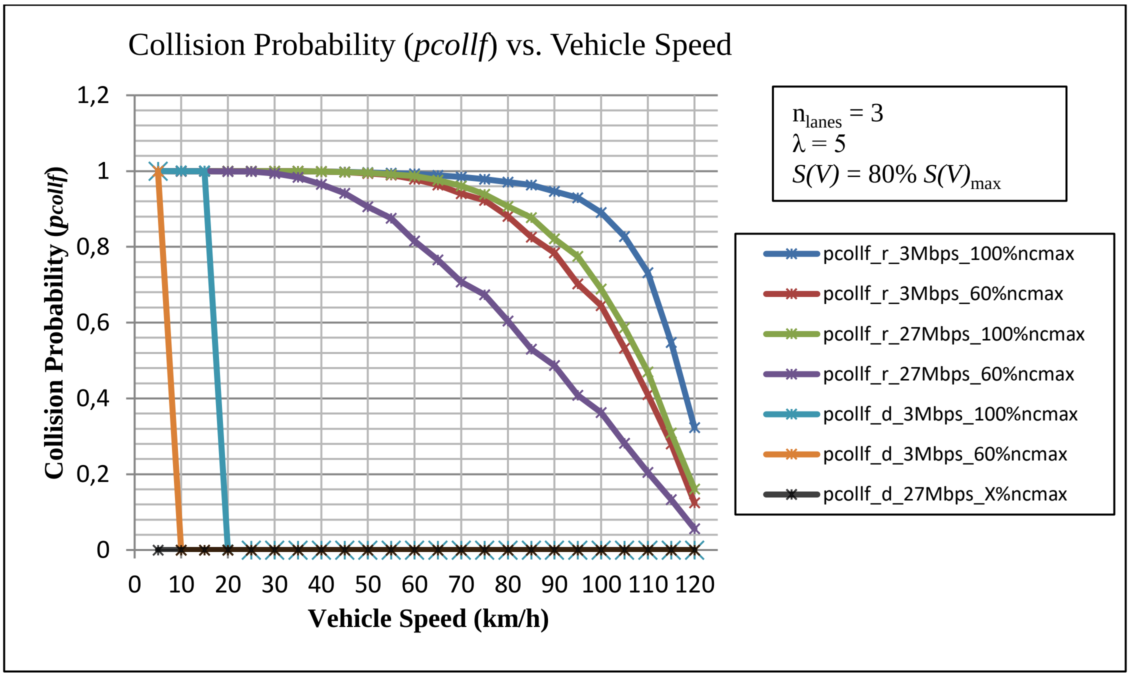

Figure 5-6. Collision probability vs. Vehicle Speed (r – random SloP slot; d – position-based SloP slot)

In Figure 5-6 it is shown several curves, for different bit rates, using different methods for choosing the SloP slot, and different percentages of the maximum number of vehicles for the given set values. If a random method is used to choose the SloP slot, the collision probability is lower when a higher bit rate is used (compare “pcollf_r_3Mbps_100%ncmax” – dark blue curve – with “pcollf_r_27Mbps_100%ncmax” – green curve). Also, in a peak hour situation (considering the maximum number of vehicles possible) the collision probability is higher since there are more vehicles wanting to transmit (compare “pcollf_r_3Mbps_100%ncmax” – dark blue curve – with “pcollf_r_3Mbps_60%ncmax” – red curve). When using the position-based method to choose the SloP slot for transmission, the results are far better. Even when using the lowest bit rate of 3 Mbps, for speeds higher than 20 km/h, the collision probability is 0 even in peak hour. When using the higher bit rate of 27 Mbps, the collision probability is always 0.

5.2.1.2.3 Medium Access Delay vs. Number of Vehicles and Vehicle Speed

Since the IDM model was used, in which the drivers tend to keep a velocity-dependent equilibrium gap to the front vehicle, the number of vehicles in a given range is dependent on the vehicle speed. Thus, the medium access delay can be plotted as a function of the number of vehicles (Figure 5-7) or the vehicle speed (Figure 5-8).

It was considered both ends of the bit rates, 3Mbps and 27 Mbps. The others will lie somewhere in the middle of those two. Observing Figure 5-7, in which the maximum number of vehicles was considered for the worst-case, when using the lowest bit rate and a random choice of SloP slot, as soon as the number of vehicles exceeds 40, the medium access delay stays approximately constant with the worst value of 127.5 ms. If, on the same conditions, the position-based choice of SloP slot is used, the medium access delay remains constant at 27.5 ms until the number of vehicles exceeds 104. Then, it rises abruptly and stays constant at 127.5 ms for 120 vehicles or more. When using the highest bit rate of 27 Mbps, and the random choice of SloP slot, the result is very similar to the lowest bit rate, but the same maximum value of 127.5 ms occurs when the number of vehicles exceeds 50. On the contrary, when using the position-based choice of SloP, the medium access delay remains constant at 27.5 ms independently of the number of vehicles present.

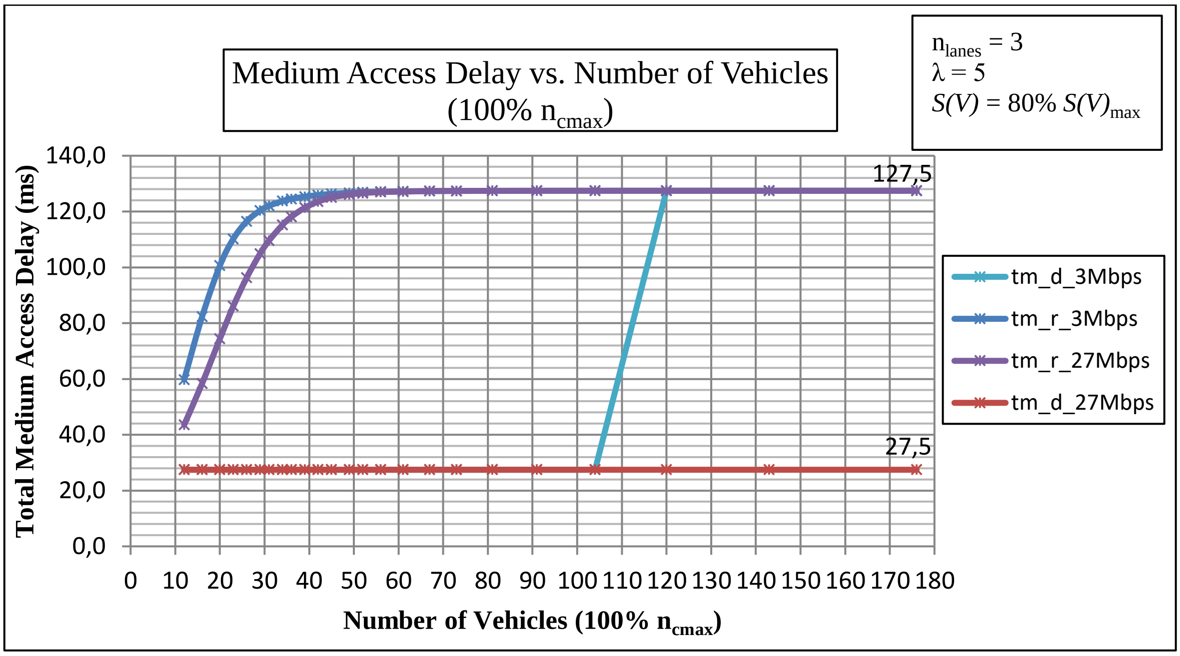

Figure 5-7. Medium Access Delay vs. Number of Vehicles (100% n_{Cmax})

When considering the medium access delay as a function of vehicle speed (Figure 5-8), in general for lower speeds the medium access delay is higher. This is due to a lower inter-vehicle spacing at those speeds, meaning there are more vehicles within the coverage range, thus leading to more medium contention. Analyzing three "high" speeds (80 km/h, 100 km/h and 120 km/h), thus with the potential of being more dangerous, when using the lowest bit rate of 3 Mbps and the maximum number of vehicles (peak hour, 100% n_{c_max}), the medium access delay can reach as high as 124.5 ms at 80 km/h, lowering to 116.5 ms at 100 km/h and 59.8 ms at 120 km/h. In a situation where only 60% of n_{c_max} are travelling on the road, the delay lowers to 107.4 ms at 80 km/h, 82.2 ms at 100 km/h and 35.9 ms at 120 km/h. If the highest bit rate of 27 Mbps is used, the results are better as expected. If a peak hour situation is considered (100% n_{c_max}), the medium access delay reaches 118.1 ms at 80 km/h, lowering to 96.3 ms at 100 km/h and 43.6 ms at 120 km/h. In a situation where only 60% of n_{c_max} are travelling on the road, the delay lowers to 82.3 ms at 80 km/h, 58.3 ms at 100 km/h and 31.2 ms at 120 km/h. All these results are considering that a random choice of SloP slot is used. However, if the position-based choice of SloP slot is used, the medium access delay remains constant at 27.5 ms for all the "high" velocities considered (even when velocity reaches as low as 20 km/h).

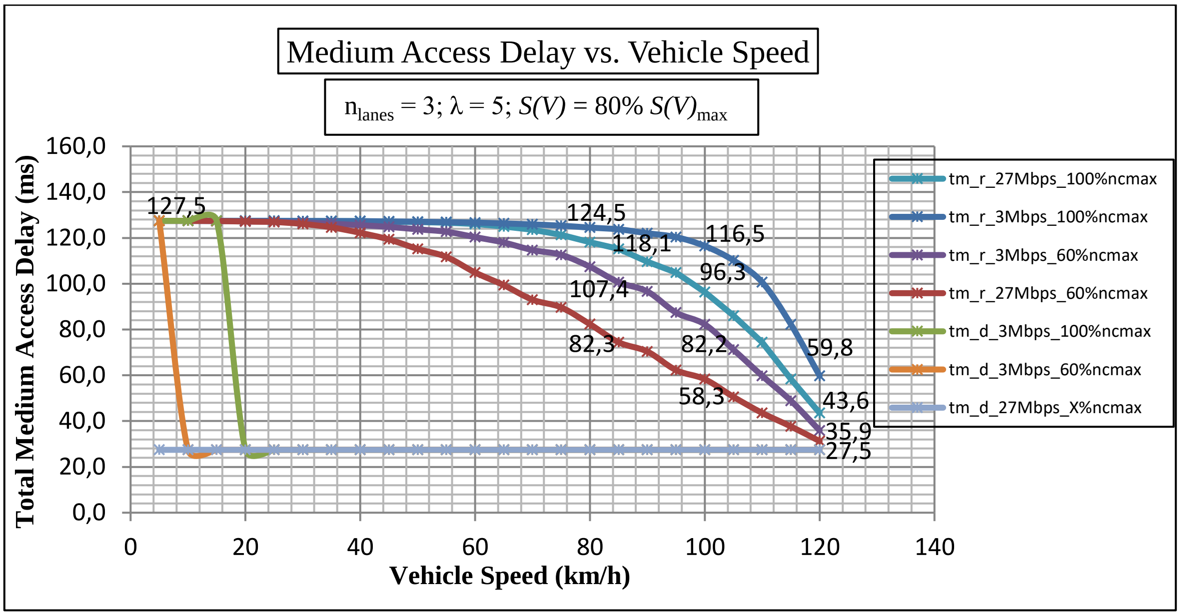

Figure 5-8. Medium Access Delay vs. Vehicle Speed

5.2.1.2.4 Medium Access Delay vs. % of maximum number of vehicles

It can be interesting to plot the medium access delay as a function of the percentage of maximum number of vehicles (% n_{c_max}), representing situations ranging from a clear way to a peak hour. Figure 5-9 shows this plot for the lowest bit rate of 3 Mbps and for different speeds. Since high speeds are more dangerous, it was chosen three of those (80 km/h, 100 km/h and 120 km/h). It can be seen that increasing the speed leads to a lower medium access delay (this is due to a less number of vehicles within the coverage range). For a fixed velocity, the delay decreases as the percentage of n_{c_max} also decreases. This is more pronounced if the speed is higher. For instance, at 120 km/h the delay at 60% of n_{c_max} is 60% of the delay at the maximum number of vehicles (100% n_{c_max}), whereas at 80 km/h the delay at 60% of n_{c_max} is 86% of the delay at the maximum number of vehicles (100% n_{c_max}). All these values are for a random choice of the SloP slot. Finally, and when using a position-based choice of SloP slot, independently of the three velocities considered, the medium access delay remains constant at 27.5 ms.

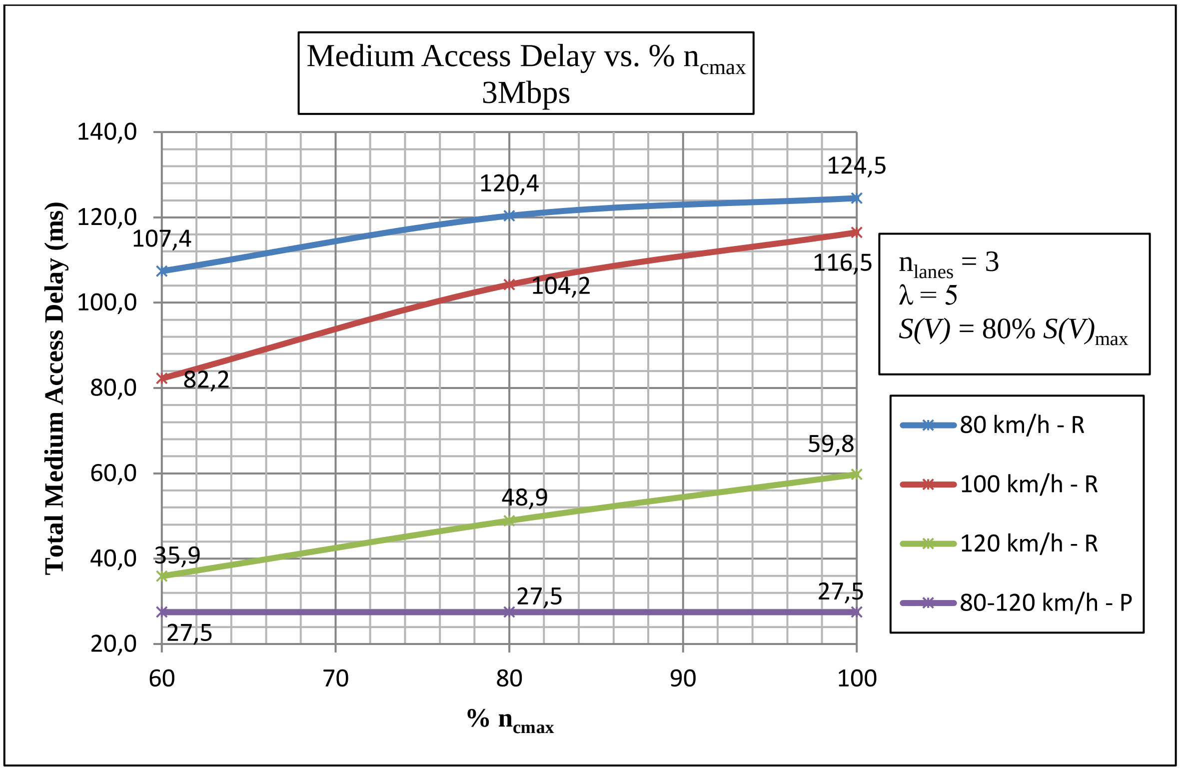

Figure 5-9. Medium Access Delay vs. Percentage of maximum number of vehicles (% n_{c_max}) – 3 Mbps

In Figure 5-10 the medium access delay is shown as a function of the percentage of maximum number of vehicles for the highest bit rate of 27 Mbps. The tendency is the same as explained above for the 3 Mbps rate, with the distinction being made at the absolute values of the medium access delay. However, when using a position-based choice of SloP slot the medium access delay has the same value as for the 3 Mbps rate.

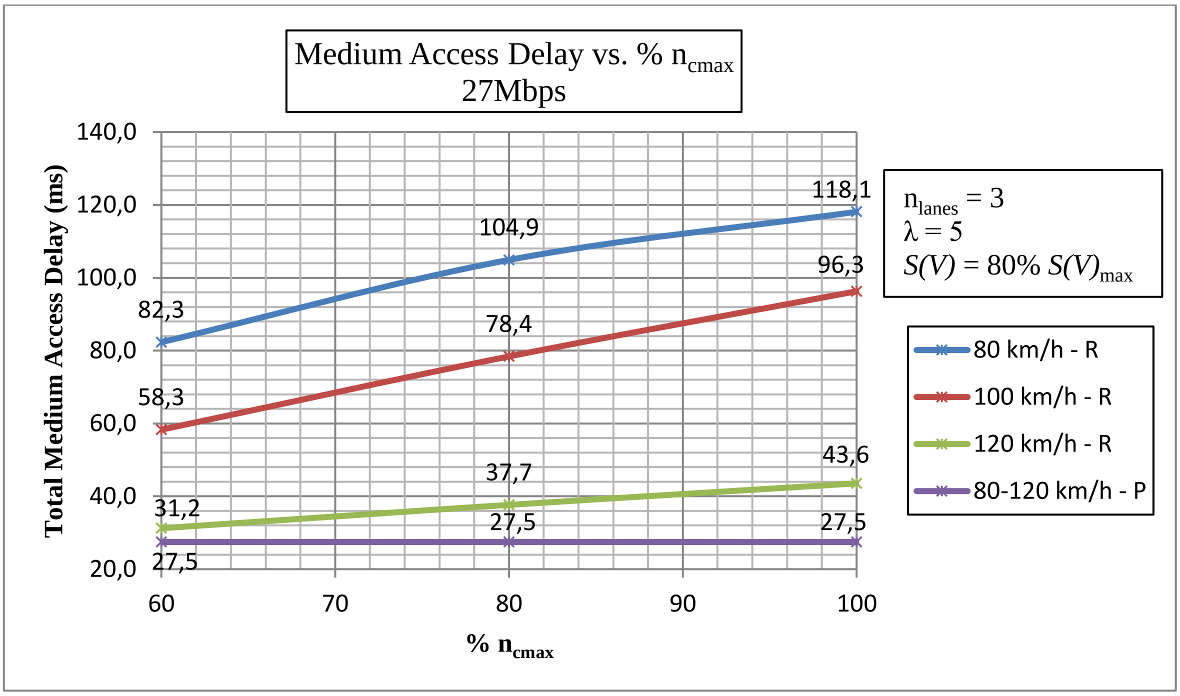

Figure 5-10. Medium Access Delay vs. Percentage of maximum number of vehicles (% n_{c_max}) – 27 Mbps

5.2.1.3 Queuing Delay

The queuing delay, t_q, is a function of the packet generation rate, λ, and the medium access delay. In what concerns the medium access delay, since it is different for each speed considered, it was used the average for all the values obtained at each speed. This will result in worst results for the queuing delay (e.g., the medium access delay at 3 Mbps, for 100% n_{c_max} and a random slot choice is on average 119.4 ms whereas at 120 km/h is 59.8 ms; if position-based slot choice is used, the medium access delay has the average value of 40 ms, whereas for speeds above 15 km/h its value is 27.5 ms). As mentioned in Chapter 2, typical frequencies of WAVE short status messages (WSMs) are in the range 5-10 Hz, whereas Cooperative Awareness Messages (CAMs) from ITS-G5 are typically broadcasted as periodic beacons with frequency of 1-10 Hz. To cover different scenarios, three distinct cases are considered for the packet generation rate:

a) A packet generation rate of 4 packets/s, meaning a periodic message is sent in four out of 10 synchronization intervals;
b) A packet generation rate of 5 packets/s, meaning a periodic message is sent every other synchronization interval (one time every 200 ms);

c) A packet generation rate of 7 packets/s, meaning a periodic message is sent in seven out of 10 synchronization intervals;

In Figure 5-11 it is shown the queuing delay in case of a random choice of SloP slot is used, whereas Figure 5-12 shows the queuing delay for the position-based choice.

In the case of a random choice of SloP slot, the queuing delay experiences an abruptly rise at a packet generation rate of about 5 packets/s. If the lowest bit rate of 3 Mbps is used, and peak hour is considered, the queuing delay rises from 90 ms at λ = 5 to 349.2 ms at λ = 7. If a clear way situation is considered (at 60% n_{c_max}), the queuing delay drops to 63.7 ms at λ = 5 and to 190.3 ms at λ = 7. At λ = 5 it represents an increase of about 41.5% in the peak hour, whereas at λ = 7 it is about an 83.5% increase. The minimum value of the queuing delay is obtained if the highest bit rate of 27 Mbps is used. At λ = 4 it has a value of 29.87 ms, rising to 46.61 ms at λ = 5, and jumping to 110.5 ms at λ = 7.

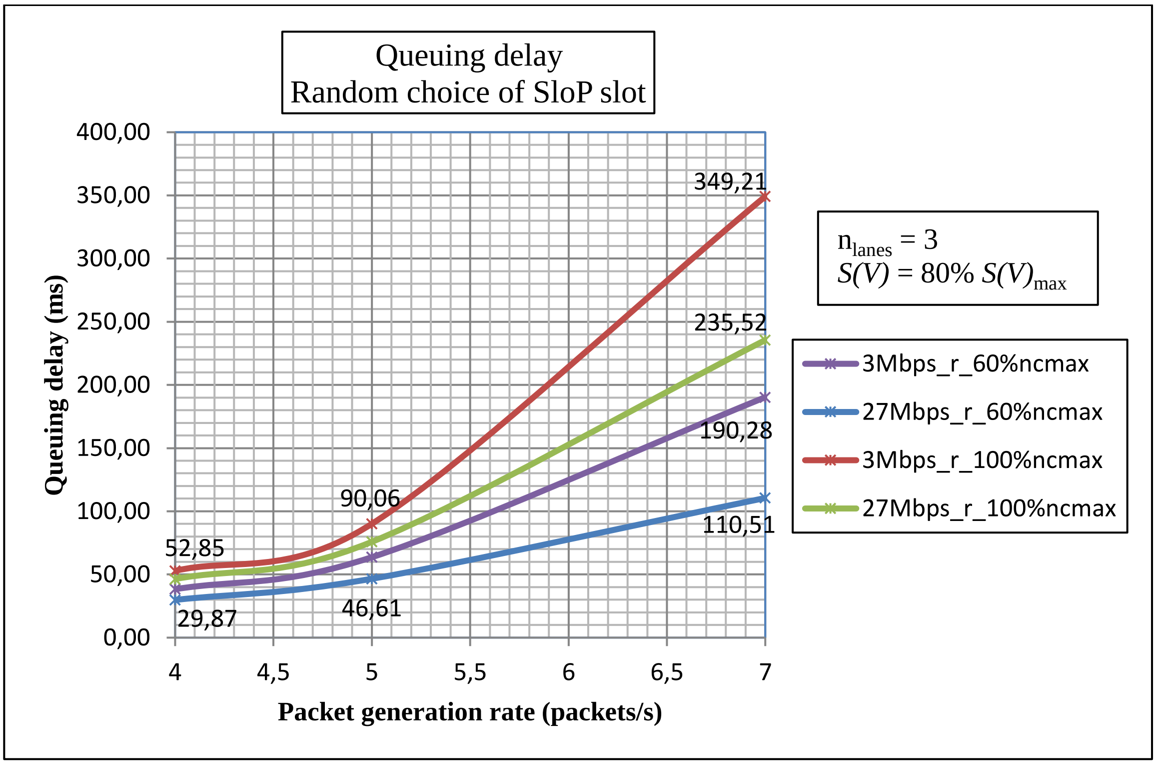

Figure 5-11. Queuing delay vs. Packet generation rate – Random choice of SloP slot

In the case of a position-based choice of the SloP slot (Figure 5-12), the values of the queuing delay are much lower in terms of absolute values. Using the bit rate of 3 Mbps, and peak hour is considered, the queuing delay rises from 8.55 ms at λ = 5 to 13.3 ms at λ = 7. This is only about 9.5% and 3.8%, respectively, of the values obtained by a random choice of SloP slot. Comparing the peak hour situation with a clear way situation, at λ = 5 it represents an increase of about 103% in the peak hour, whereas at λ = 7 it is about a 108.8% increase. If the highest bit rate of 27 Mbps is used, the values are the same for peak hour or clear way, and are 1.69 ms at λ = 4, rising to 2.18 ms at λ = 5, and to 3.27 ms at λ = 7. At λ = 7 this is only about 1.4% of the value obtained by a random choice of SloP slot at peak hour.

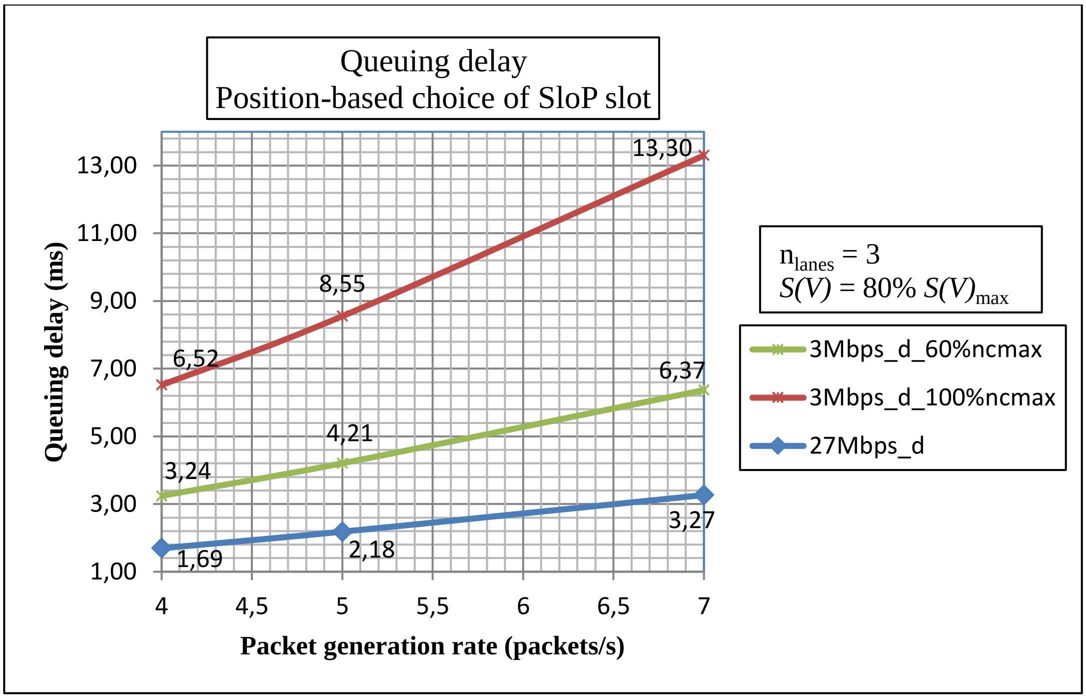

Figure 5-12. Queuing delay vs. Packet generation rate – Position-based choice of SloP slot

5.2.1.4 Total End-to-End Delay

As already mentioned, the MAC delivery latency (end-to-end delay) is the sum of the medium access delay along with the queuing delay. This is summarized in the following tables, for the three packet generation rates referred in the previous section. Also, in each table, the end-to-end delay is given for the lowest bit rate (3 Mbps) and the highest bit rate (27 Mbps), in peak hour (100% n_{c_max}) and clear way (60% n_{c_max}) scenarios. The delay is obtained for three different vehicle speeds (highest ones since they represent more dangerous situations), 80 km/h, 100 km/h, and 120 km/h. Finally, the delay is compared when it is used a random method of choosing the SloP slot to transmit, or when it is used the position-based method referred in Chapter 4.

Table 5-2. Total end-to-end delay (milliseconds) at λ = 7.

λ = 7	RANDOM SLOT CHOICE			POSITION-BASED SLOT CHOICE		
	80 km/h	100 km/h	120 km/h	80 km/h	100 km/h	120 km/h
3Mbps, 60% n_{c_max}	304.1	279.8	228.5	33.8	33.8	33.8
3Mbps, 100% n_{c_max}	475.9	470.7	414.9	40.8	40.8	40.8
27Mbps, 60% n_{c_max}	197.2	172.9	142.8	30.7	30.7	30.7
27Mbps, 100% n_{c_max}	355.7	335.7	282.1	30.7	30.7	30.7

Table 5-3. Total end-to-end delay (milliseconds) at λ = 5.

λ = 5	RANDOM SLOT CHOICE			POSITION-BASED SLOT CHOICE		
	80 km/h	100 km/h	120 km/h	80 km/h	100 km/h	120 km/h
3Mbps, 60% n_{c_max}	171.1	145.9	99.6	31.7	31.7	31.7
3Mbps, 100% n_{c_max}	214.6	206.5	149.8	36.0	36.0	36.0
27Mbps, 60% n_{c_max}	128.9	104.9	77.9	29.6	29.6	29.6
27Mbps, 100% n_{c_max}	193.9	172.1	119.4	29.6	29.6	29.6

Table 5-4. Total end-to-end delay (milliseconds) at λ = 4.

λ = 4	RANDOM SLOT CHOICE			POSITION-BASED SLOT CHOICE		
	80 km/h	100 km/h	120 km/h	80 km/h	100 km/h	120 km/h
3Mbps, 60% n_{c_max}	139.7	114.9	72.9	30.7	30.7	30.7
3Mbps, 100% n_{c_max}	174.3	164.0	108.5	34.0	34.0	34.0
27Mbps, 60% n_{c_max}	108.1	85.0	60.5	29.1	29.1	29.1
27Mbps, 100% n_{c_max}	161.6	138.6	87.9	29.1	29.1	29.1

When using the random slot choice of SloP slot, for a packet generation rate of seven packets per second (λ = 7), the total end-to-end delay seems excessive for certain type of safety applications. However, if the packet generation rate lowers (to λ = 5 or λ = 4), the method may be used and fulfill the timing requirements for some safety applications. It is notorious the improvement in the total end-to-end delay when using the position-based method to choose the SloP slot when having a message to transmit. In this case, independently of the packet generation rate, the timing requirements are perfectly fulfilled for all safety applications. According to (JOHNSON, RUMMER, 1971), driver reaction time varies between 0.4 s and 2.7 s. In (NEKOVEE, 2009) it was used the average value of 1 s, and the maximum acceptable single-hop latency was derived so that rear-end collision can be avoided after a sudden brake. For the dry asphalted road (most stringent), at 10 km/h it is about 300 ms, whereas at 100 km/h is about 2.83 s. Taking into account the results obtained in this section, the I-TDMA solution seems to cope well with this type of safety applications.

5.2.2 Alternative V2V Based Solution

For evaluating the alternative V2V-based solution presented in Section 4.3 (see Figure 4-15), the duration of safety frames should be determined, in order to find how many slots can exist in the CCH interval after the guard interval (GI). The GI is defined in the IEEE 1609.4 standard (IEEE WAVE, 2010).

A common safety application is EEBL (Emergency Electronic Brake Lights). Using the solution presented in Section 4.1.3, the EEBL safety message payload size will be 41 bits at the application layer. The fields and respective number of bits are shown in Table 5-5.

Table 5-5. Application Layer fields and size of EEBL safety message.

FIELDS	SIZE (BITS)
Event Lifetime, t_{lf}, (in number of Sync. Int.)	16
Vehicle Position (in tenths of meters)	20
Distance of Interest (d_E)	4
Vehicle Heading (f_g)	1

In terms of PHY layer parameters, it is assumed a channel spacing of 10 MHz and Orthogonal Frequency Division Multiplexing (OFDM) modulation, in which the mandatory bit rates are 3, 6, and 12 Mbps, and the maximum allowed is 27 Mbps. The standard MAC layer frame used, as well as the OFDM PHY frame is shown in Figure 5-13 and Figure 5-14, respectively.

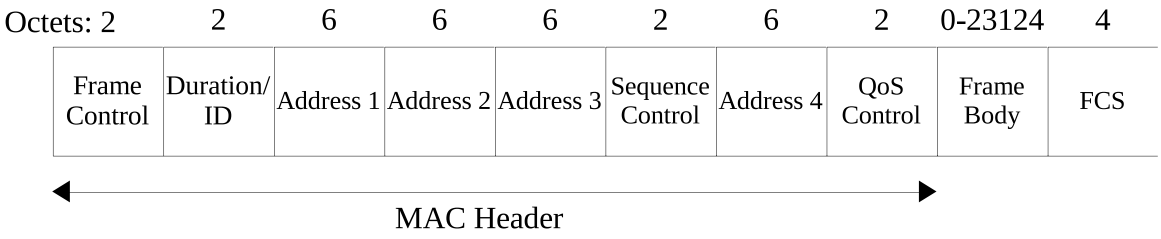

Figure 5-13. IEEE 802.11 Standard MAC frame (IEEE 802.11, 2007).

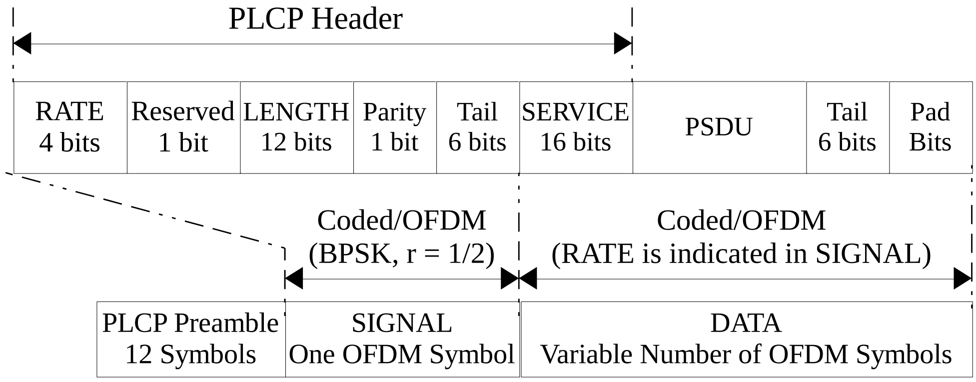

Figure 5-14. IEEE 802.11 Standard OFDM PHY frame (IEEE 802.11, 2007).

Adding to the EEBL application frame the MAC layer bits (288bits), as defined in IEEE 802.11 standard (IEEE 802.11, 2007) (Figure 5-13), as well as adding the PHY fields (Figure 5-14), it is possible to determine the frames transmission times, for each bit rate, for the referred safety frame, as seen in Table 5-6.

Table 5-6. EEBL safety message transmission time.

Data rate (Mbps)	**EEBL safety message duration (µs)**
3	154.1
6	96.8
12	64.4
27	48.1

Relatively to the Event Period (EP) and Warning Message Period (WMP), the shorter the WMP, more slots are available for new events (transmitted in EP). However, the inferior limit is dictated by the possible number of vehicles that could try to allocate a WMP normal slot to rebroadcast a safety event. Thus, using Eq. (4.15), and replacing the distance of interest, d_E, for the transmission range of the message issued by the generating vehicle as a reaction to an event, $d_I(t_2)$, for the worst-case analysis, the number of vehicles that could try perform slot allocation within WMP can be calculated. The inferior limit imposed to determine the needed WMP normal slots should be fixed for the case where there are more vehicles (lower velocities, translating into less inter-vehicle spacing). However, the lower the velocity the lower the chance of generating a safety event, and the lower the risk posed to human health. Thus, the minimum velocity for a vehicle is defined as being 20 km/h with an inter-vehicle spacing of 10 m. By guaranteeing the maximum number of normal slots within WMP, it could be guaranteed that the safety event is rebroadcasted (exception is when all vehicles belonging to the same super slot have the same position – side by side in each lane – and the same velocity, and derive the same random number within the normal slot to start transmission).

Some parameters are defined in the standard. These are shown in Table 5-7. For safety messages (highest access category, AC = Voice) the parameters CW_{min}, CW_{max} and AIFSN shown in the standard contain values of 3, 7 and 2 respectively. Also, when using OFDM at PHY layer, with a channel spacing of 10 MHz, the parameters needed to determine CW_{min} and CW_{max} are defined in the standard, as well as the beginning values that should precede a frame transmission, and these are shown in Table 5-8.

Table 5-7. EDCA parameter set used on the CCH (IEEE WAVE, 2010).

AC	CWmin	Cwmax	AIFSN
Background	aCWmin	aCWmax	9
Best effort	(aCWmin+1)/2 – 1	aCWmin	6
Video	(aCWmin+1)/4 – 1	(aCWmin+1)/2 – 1	3
Voice	(aCWmin+1)/4 – 1	(aCWmin+1)/2 – 1	2

Table 5-8. OFDM PHY characteristics (IEEE 802.11, 2007) (channel spacing 10MHz).

Characteristics	**Value**
aSlotTime	13 μs
aSIFSTime	32 μs
aCWmin	15
aCWmax	1023

If one knows the frames transmission times and the normal slots needed, the WMP duration may be computed by multiplying both. The slot duration comprises not only the frame transmission time, but also the duration of SIFS, plus the duration of two slot times, plus the maximum contention window duration. This is shown in Eq. (5.14), and an example is given for 3 Mbps in Table 5-9.

$$Slot\ duration = Frame\ TX\ time + SIFS + 2 \cdot aSlotTime + CW_{max} \cdot aSlotTime \quad (5.14)$$

Table 5-9. Times used for computing slot duration for 3 Mbps.

Frame TX time (μs)	**2·aSlotTime (μs)**	**CW_{max}·aSlotTime (μs)**	**Slot duration (μs)**
154.1	26	91	303.1

The EP duration may be known by subtracting the duration of the WMP to the CCH interval (minus the G.I.) duration. Finally, by dividing the EP duration for the slot duration needed, it is possible to know the number of slots available in EP.

In Table 5-10 it is shown two different highway traffic scenarios in which the duration as well as the number of slots of the WMP and EP are calculated. Scenario A is a normal traffic situation, where vehicles are separated by 40 m. In scenario B it is considered a traffic jam, with vehicle separation of 10 m, as defined in (EICHLER, 2007). Also, these values are 80% of those obtained from Eq. (5.2) when considering that vehicles are moving at approximately 85 km/h and 20 km/h, respectively. This percentage aims to simulate a less cautious driving.

Table 5-10. Highway Traffic Scenarios A (normal traffic) and B (traffic jam).

Scenario A (normal traffic ~ 85km/h)		**Scenario B (traffic jam~ 20km/h)**	
c_{length}	4,5 m	c_{length}	4,5 m
$c_{spacing}$	40 m	$c_{spacing}$	10 m
$d_l(t_2)$	500 m	$d_l(t_2)$	500 m
n_{lanes}	3	n_{lanes}	3
n_{dE}	33	n_{dE}	103
$WMP_{duration}$(3Mbps): 31.2 ms			
$WMP_{duration}$(6 Mbps): 25.3 ms			
$WMP_{duration}$(12 Mbps): 22 ms			
$WMP_{duration}$(27 Mbps): 20.3 ms			
$EP_{duration}$(3 Mbps): 14.8 ms			
$EP_{duration}$(6 Mbps): 20.7 ms			
$EP_{duration}$(12 Mbps): 24 ms			
$EP_{duration}$(27 Mbps): 25.7 ms			
EP_{slots}(3 Mbps): 48			
EP_{slots}(6 Mbps): 84			
EP_{slots}(12 Mbps): 112			
EP_{slots}(27 Mbps): 130			

In both scenarios, as mentioned earlier, the WMP duration is the same, and is obtained by determining the number of vehicles at the range of a possible event generator (for the worst-case hypothesis, i.e., $d_E = d_l(t_2)$ in Eq. (4.15), and travelling at 20 km/h, with an inter-vehicle spacing of 10 m. In this case, and using the average vehicle length and coverage range shown in Table 5-10, the number of vehicles will be 103, thus leading to 103 normal slots reserved for WMP.

Analyzing scenario A, the number of vehicles following an eventual generator, and possible receivers of a broadcast, is 33. For all the bit rates, the number of slots available within EP is greater than the number of vehicles. So, with a deterministic slot allocation procedure, it is possible to avoid contention even if all the vehicles want to transmit a message at the same time. Consequently, the protocol performs very well in this situation.

Analyzing now scenario B, the number of vehicles following an eventual generator, and possible receivers of a broadcast, is 103. For the different bit rates, it can be seen that for 3 Mbps and 6 Mbps there are 48 and 84 slots respectively in the Event Period. Therefore, if all vehicles want to transmit a message, even with a deterministic choice of the slot, collisions will occur. It should be noted that this is assuming a maximum number of vehicles (for the corresponding inter-vehicle spacing). However, there may be cases where the vehicles' number is inferior, thus leading to a better performance of the protocol.

For the other bit rates (12 Mbps and 27 Mbps), the number of slots available within EP is 112 and 130 respectively. So, with a proper slot allocation procedure, it is possible to avoid contention even if all the vehicles want to transmit a message at the same time. Consequently, the protocol performs very well in this situation.

In this chapter it was done a thoroughly performance evaluation of the devised protocols, particularly the MAC end-to-end delay. The main goal was comparing this performance metric for two distinct situations. The first situation assumed that a vehicle willing to transmit a message over the control channel (CCH), will do so by performing a random choice within the slots contained in the period reserved for vehicle's messages. In the second situation, the vehicle uses a position-based slot choice in order to perform message transmission. This choice is based on its current position, which is derived from the last GPS coordinate obtained, and also based on the information provided by the RSU on its beacon, in particular the RSU position, the number of lanes and number of slots available. This information is sent in the beginning of every CCH interval by the RSU. For determining the total end-to-end delay, the queuing delay was also taken into account. This means not using the saturated model, since it restricts the end-to-end delay performance full study by not considering the impact of the MAC layer queue.

The results, when analyzing several distinct cases, show that the total medium access delay is significantly reduced when using the position-based slot choice situation. When analyzing the total end-to-end delay, and considering a packet generation rate of 5 packets/s, a standard bit rate of 3 Mbps/s, a vehicles' velocity of 100 km/h, and a rush-hour situation, the delay is 207 ms for random slot choice versus 36 ms for a position-based slot choice (a reduction of about 83%). In terms of collision probability, when using the position-based method to choose the SloP slot for transmission, the results are far better than when a random method is used. Even when using the lowest bit rate of 3 Mbps, for speeds higher than 20 km/h, the collision probability is 0 even in peak hour. When using the higher bit rate of 27 Mbps, the collision probability is always 0. In terms of the queuing delay, if a position-based choice of the SloP slot is used the total queuing delay is much lower in terms of absolute values. Also, in the case of a random choice of SloP slot, the queuing delay experiences an abruptly rise at a packet generation rate of about 5 packets/s.

CHAPTER 6

CONCLUSIONS AND FUTURE WORK

Summary

This final chapter includes the conclusions and contributions of the present work in terms of MAC protocols aspects, and the delay associated, for safety-critical information exchanged in vehicular networks. Future lines of research are also outlined.

6.1 Conclusions

The dissemination of technology in vehicles and the consequent dissemination of vehicular communication networks transform safety applications in a major priority in order to reduce road traffic accidents and human being fatalities in the following years.

Safety-critical applications, e.g., sudden hard-brake or collision warning, require typically low channel access delay with a well-defined upper bound. This includes an overload situation, in which the medium resources are fully occupied and a new safety-event generator needs to transmit the corresponding message timely. These requirements pose the burden of message timeliness on the transmissions' scheduling and medium reservation functions performed by the MAC layer. It was noticed that such goals may not be fulfilled even when using implementations in conformance with the standards. For instance, the WAVE architecture accounts support for safety messages within vehicular networks. However, high collision probability is not negligible, particularly in dense scenarios, which may jeopardize the timing constraints of safety messages.

In the first part of this thesis the context for communications in vehicular networks was established, and it was introduced the motivation for utilization of safety services as a main priority. Afterwards, an overview of the real-time requirements and the main characteristics and applications for vehicular communication networks was done, and it was also presented the current related standards and projects. Several MAC protocols were explained and their limitations identified and discussed. The major problems for vehicular time-critical MAC protocols were discussed and the substantiation for the thesis was presented. The data traffic models found in vehicular networks (periodic messages predominantly coexisting with event-triggered warnings) lead to a time-triggered communication model with broadcasts. A time slotted MAC approach is an appropriate solution to guarantee timely delivery of safety messages.

The second part of this PhD thesis comprised the main work of deriving improved MAC techniques, and it included the design of an infrastructure-based MAC protocol in order to timely deliver event-driven safety messages, and the design of a position-based method to carefully choose the slot for transmission, in order to reduce significantly the collision probability and consequently the total latency. An alternative solution, for "dark" zones, in which RSU coverage is not present, and relying solely on V2V communications to delivery safety messages when needed, was also addressed. The end-to-end delay performance metric, including both the medium access delay and the queuing delay, was also determined and an evaluation model was outlined.

When designing the I-TDMA MAC protocol based solution, it was taken into account the inclusion of a feature typically used in time-slotted self-organizing MAC protocols, contained in several VANETs approaches. This feature comprises having the nodes transmitting information about which other nodes they receive information from, or their perception of the current slot allocations. This is done to prevent unintentional slot reuse by hidden terminals.

Regarding IEEE 802.11p/P1609.4 MAC utilization and the specificity of CCH and SCH usage, the assumed requirement of using the CCH for safety information dissemination can strongly affect the end-to-end delay depending on the scenario considered (i.e., at what instant the safety event has occurred). If the achieved delay is not admissible, the utilization of a mechanism forcing the use of CCH more often than SCH, i.e., stay tuned in CCH in some SCH intervals, could be a solution.

By using RSUs to rebroadcast the safety message, the problem resides in the initial broadcast, since in the subsequent ones contention is avoided. Adding to this, if a careful slot choice is used by vehicles needing to transmit a message, collisions can be further reduced, and a smaller upper bound to the end-to-end delay is achievable.

The analysis of figures in Section 5.2 can give us some important conclusions.

- The number of slots available for safety-related messages transmission increases as the bit rate used increases. So, for higher bit rates the possible number of simultaneous transmissions is higher and the collision probability is reduced. This seems obvious but needs to be computed as it was done. Also, the number of slots is a function of the maximum message length, or message duration, it is intended to be used. If needed, the devised beacon frames emitted from the RSUs can still be appended with extra payload fields. If the current devised payload is doubled in length, only one slot is lost within the slotted period (SloP) reserved for vehicles, in the three lower WAVE bit rates. If the latency achieved is not admissible, an eventual solution may be to work at a higher bit rate, thus reducing the medium access delay.
- When following the intelligent driver model, in which drivers tend to keep a velocity-dependent equilibrium gap to the front vehicle, the inter-vehicle spacing increases as the vehicles' velocity increases. This means the total number of vehicles within the

coverage area of a RSUs decreases for higher speeds (higher inter-vehicle spacing). This is important since, for higher velocities, the danger and risk posed by an accident is higher, and thus the total number of slots available will be object of contention by less vehicles.

- The collision probability (probability of at least two OBUs having messages to transmit and both choose the same slot), p_{collf}, decreases with the increase in vehicle' speed and also with the increase in the bit rate used. If the random method is used for slot choice the collision probability is higher than 0.9 for velocities lower than 80 km/h if lower bit rates are used. Contrarily, if the position-based method is used to choose the transmission slot, the collision probability is 0 for speeds higher than 20 km/h, even for the lower bit rates and for peak hour traffic situation.
- Analyzing the higher velocities, which are more dangerous, from 80 km/h to 120 km/h, the average medium access delay, considering the specificity of using only the CCH to broadcast safety-event messages, varies from about 31 ms to 124.5 ms when using the random method for slot choice. The large variation interval is related with varying also the traffic situation – clear or peak hour – as well as using the extreme WAVE standard bit rates – 27 Mbps and 3 Mbps. In general, as the vehicles' velocity increases, the average medium access delay decreases. If the position-based method is used, the average medium access delay is reduced and remains constant at 27.5 ms. This is significantly lower than the typical latency requirements of safety-critical applications – 100 ms.
- Relatively to the queuing delay, under finite load conditions and having each station modeled with an M/G/1 queue, the higher the packet generation rate is, the higher the queuing delay will be. If the random method is used for transmission slot choice, the queuing delay rises abruptly at about 5 packets/s, with absolute values reaching about 236 ms (at 27 Mbps) and 349 ms (at 3 Mbps) for a generation rate of 7 packets/s, and considering peak hour traffic. Since the short status messages used in WAVE have generation rates in the range 5-10 Hz this could be problematic. However, if the position-based method is used, the increase is not so abrupt, and the absolute maximum value is 13.3 ms for the same conditions referred previously. So, for the position-based method a higher packet generation rate may be supported without increasing the queuing delay abruptly and keeping the total latency small.

- Finally, the total MAC delivery latency (end-to-end delay), when considering vehicles' velocity between 80 km/h and 120 km/h, and ranging from a bit rate of 27 Mbps with clear way traffic to a bit rate of 3 Mbps with peak hour traffic, and a packet generation rate from 4 to 7 packets/s, varies from about 61 ms to 476 ms for random slot choice, and varies from about 29 ms to 40 ms for position-based slot choice. The traffic condition has a higher impact, in terms of relative increase, on the total end-to-end delay at higher bit rates, for the same speed. Also, the traffic condition has a higher impact, in terms of relative increase, on the total end-to-end delay at higher velocities, for the same bit rate.

Taking into account the results obtained in the previous chapter, the I-TDMA solution seems to cope well with this type of safety applications.

6.2 Future Work

The designed MAC protocol with "deterministic" slot choice addresses timely delivery of safety messages in a highway scenario and takes into account the WAVE standard specificity. However, there are still open issues requiring further investigation.

MAC protocol overload

As said previously the MAC protocol should cope with an overload situation. This means it should be guaranteed that a new event generating a safety message, which transmission delay is critical, is not blocked (delayed) if a slot is not available and immediate access is granted. Despite the position-based method takes into account the maximum number of vehicles present within the coverage range, and the results are quite satisfactory, an improved SloP slot choice by OBUs to reduce collision probability of safety events can be taken. Since it not likely that several simultaneous events occur within one CCH interval, a small number of slots may be reserved only for safety events broadcast. Future work includes performing exact calculations on the improved SloP slot choice. However, since the number of reserved slots for safety events broadcast will be small, the results should be very similar to those obtained in Chapter 5.

Collision probability

Since the medium access delay depends heavily on the collision probability when performing a slot choice to transmit a safety related message, a way of minimizing the collision probability could be having each RSU transmitting in its beacon (or vehicle in its periodic status messages) the status of each slot within SloP in the previous CCH interval.

Traffic model

The IDM model uses several assumptions, for e.g., vehicles travel at the same speed. Further investigation includes using a different traffic mobility model, considering vehicles travelling at different speeds, namely, one speed for each lane (the leftmost lane with the highest speed and the rightmost lane with the lowest speed).

Performance evaluation

Another performance metric is to compute the protocol overhead, i.e., data that is necessary to transmit in order to the designed protocol functions continually (not the overhead existent in all protocols due to headers and trailers of OSI layers). There is a tradeoff between protocol overhead and reception rate. If the numerical overhead is low but fewer nodes receive packets, the gain is not worth. More significant metrics for the evaluation of VANET's overheads should be the reception rate and is the ratio between the inter-packet (time of consecutive received packets) and the time required for transmission of the payload (ETSI, 2012).

Simulation

A mobility model needs to be well defined/generated. This means it should be as realistic as the network that will be simulated, in order to achieve good simulation results. Further work would be to find an appropriate simulation tool (e.g., VNS, NS-3 or OMNET++) in order to perform simulations with different scenarios that could assess the viability of the designed protocol.

Synchronization

In this thesis it is assumed that nodes share a common synchronization source (absolute external time reference) relying mainly in GPS. However, further investigation needs to be done to outline a synchronization procedure in case a GPS module/signal is not available.

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APPENDIX A

LIST OF PUBLICATIONS

Summary

This appendix includes the list of publications done within the execution of this work.

Year: 2007

Title: *Using time-triggered communications over IEEE 802.15.4*

Authors: Nuno Ferreira, José Fonseca.

Conference: IEEE Conference, ETFA 2007; 25-28 September 2007, Pages: 1384-1387, ISBN: 978-1-4244-0825-2.

Abstract: IEEE802.15.4 is used for low-data-rate connectivity among fixed or moving devices, with low-cost and low-power consumption, in applications in residential and industrial environment, e.g. home automation and automotive. The Flexible Time-Triggered paradigm (FTT) allows different types of traffic (time and event-triggered, hard and soft real-time) with temporal isolation between each other and a flexible handling of time-triggered traffic with dynamic communication requirements. This paper proposes a preliminary solution for the transmission of real-time time-triggered traffic over the 802.15.4 standard, as a beginning to implement a full FTT protocol. The envisaged applications are in the field of home automation with real-time requirements to convey life support signals and in infrastructure or vehicle to vehicle communications (I2V and V2V).

Year: 2008

Title: *On the adequacy of 802.11p MAC protocols to support safety services in ITS*

Authors: Nuno Ferreira, José Fonseca, Jorge Gomes.

Conference: IEEE Conference, ETFA 2008; 15-18 September 2008, ISBN: 978-1-4244-1505-2.

Abstract: The use of IEEE 802.11p for supporting intelligent transportation systems (ITS) enables enhancing the drive experience to provide vehicle users with useful information related to road efficiency and public safety. Safety services, such as collision or sudden hard braking warning, are used to improve passenger safety and reduce fatalities. Along with the delay-critical nature of those services, the highly dynamic communication environment of vehicular networks demand an efficient medium access control (MAC) protocol to assure minimal transmission collisions. This work-in-progress paper presents a preliminary study on the adequacy of existent 802.11p based MAC protocols regarding safety applications, and proposes ideas to implement such services in an effective way assuming an infrastructure based operation mode.

Year: 2009

Title: *WAVE Based Architecture for Safety Services Deployment in Vehicular Networks*

Authors: Nuno Ferreira, Tiago Meireles, José Fonseca, João Matos, Jorge Gomes.

Conference: 8th IFAC International Conference on Fieldbuses and Networks in Industrial & Embedded Systems; 20-22 May 2009, ISBN: 978-1-6178-2873-7.

Abstract: Vehicle manufacturers, highway concessionaries, governments and academic research are cooperating to find the best solution to add safety services relying on vehicle to vehicle communication systems (V2V) and among vehicles and the infrastructure (V2I) located on the roadside. Safety services, such as collision or sudden hard braking warning have delay-critical requirements. This paper proposes a WAVE (Wireless Access for Vehicular Environment) based model and a MAC protocol to disseminate time-critical messages for safety services in highways where the Road Side Units (RSUs) are not present in the instant a safety event is generated and, consequently, the message dissemination is done only through vehicles. The model allows to determine the retransmission slot number and the model's feasibility is somewhat evaluated by analysing the maximum number of available slots for a typical scenario.

Year: 2009

Title: *An RSU coordination scheme for WAVE safety services support*

Authors: Nuno Ferreira, Tiago Meireles, José Fonseca.

Conference: IEEE Conference, ETFA 2009; 22-26 September 2009, ISBN: 978-1-4244-2727-7.

Abstract: The use of wireless communication technologies to increase road safety is rising within the automobile world. Vehicle to Vehicle (V2V) communications is a very promising field but the slow vehicle renewal rate combined with the current world economic crisis turns V2V into a distant scenario. A more viable solution relies on Infrastructure to Vehicle Communications (I2V) and the use of the Wireless Access for Vehicular Environment (WAVE) standard, specifically tailored for delivering safety and multimedia messages in a highly dynamic communication environment. This work-in-progress paper addresses an open issue in a previous presented infrastructure based solution: the beacon coordination between adjacent Road Side Units (RSUs) and also a safety message retransmission mechanism performed by such RSUs.

Year: 2009

Title: *Development of Vehicular Communications based on WAVE (802.11p)*

Authors: Tiago Meireles, Nuno Ferreira, José Fonseca, João Matos.

Conference: 8th International Conference and Workshop on Ambient Intelligence and Embedded Systems, Funchal, Portugal, September 2009.

Abstract: The use of communication technology is rising within the automobile world. Vehicle manufacturers, highway concessionaries, governments, academic researchers and Industry cooperate in order to develop vehicle communication systems, offering safety services that can reduce the number of road accidents, as well as providing multimedia entertainment services to vehicle passengers. Such communication systems, when embedded on vehicles, will still take many years before having a significant impact on everyday driver habits, due to the current vehicle renewal rate, which presents a large obstacle to the deployment of safety services with pure vehicle to vehicle communications (V2V) networks. We propose a Wireless Access for Vehicular Environments (WAVE) based mixed V2V and Vehicle to Infrastructure (V2I) communications solution for the transitional period, using a simple add-on system to the vehicle. Safety services, such as collision or hard-braking warning, have delay critical requirements. This paper describes two proposals for a WAVE based architecture and medium access protocol (MAC) to disseminate time-critical messages for safety services in highways, as well as a prototype for a WAVE compliant communication system that is being currently developed.

Year: 2010

Title: *A 802.11p prototype implementation*

Authors: Duarte Carona, António Serrador, Pedro Mar, Ricardo Abreu, Nuno Ferreira, Tiago Meireles, João Matos, Jorge Lopes.

Conference: IEEE Intelligent Vehicles Symposium, San Diego, USA, June 2010, ISBN: 978-1-4244-7866-8.

Abstract: This paper presents an IEEE 802.11p full-stack prototype implementation to data exchange among vehicles and between vehicles and the roadway infrastructures. The prototype architecture is based on FPGAs for Intermediate Frequency (IF) and base band purposes, using 802.11a based transceivers for RF interfaces. Power amplifiers were also addressed, by using commercial and in-house solutions. This implementation aims to provide technical solutions for Intelligent Transportation Systems (ITS) field, namely for tolling and traffic management related services, in order to promote safety, mobility and driving comfort through the dynamic and real-time cooperation among vehicles and/or between vehicles and infrastructures. The performance of the proposed scheme is tested under realistic urban and suburban driving conditions. Preliminary results are promising, since they comply with most of the 802.11p standard requirements.

Year: 2011
Title: *On the End-to-End Delay Analysis for an IEEE 802.11P/WAVE Protocol*
Authors: Nuno Ferreira, José Fonseca.
Conference: IEEE SCVT (Symposium on Communications and Vehicular Technology), Ghent, Belgium, November 2011, ISBN: 978-1-4577-1288-3.
Abstract: The use of IEEE 802.11p for supporting intelligent transportation systems (ITS) allows a wide spectrum of applications providing vehicle occupants useful information related to public safety and road efficiency. The Wireless Access for Vehicular Environment (WAVE) standard is specifically tailored for delivering safety and multimedia messages in a highly dynamic vehicular communication environment. Such dynamic characteristics along with the delay-critical nature of safety services turn the medium access control protocol (MAC) timings very important. Therefore, it becomes of great interest to analyze a major performance metric, the end-to-end delay.

Year: 2015
Title: *Improving Safety Message Delivery through RSU's Coordination in Vehicular Networks*
Authors: Nuno Ferreira, José Fonseca.
Conference: 11th IEEE WFCS 2015, Palma de Mallorca, Spain, May 2015, ISBN: 978-1-4799-8244-8.
Abstract: Modern society lives surrounded by technology intended for enhancing human commodity, entertainment and safety. The use of novel technological solutions in transportation led to a relatively new field often called Intelligent Transportation Systems (ITS). Due to its highly dynamic nature, wireless communications are applied to implement

vehicular communication systems. The concern of reducing road injuries/fatalities is of utmost importance, being nowadays a public health question. This led the development of vehicular communication standards focused in safety-related applications. These, demand typically low channel access delay with a well-defined upper bound, which is mainly addressed in the Medium Access Control (MAC) layer. This paper emphasizes some key points favoring the use of an infrastructural architecture with full Road Side Unit (RSU) coverage, presents an overview of the used time-slotted oriented MAC approach based on the Wireless Access in Vehicular Environment (WAVE) standard, addresses the issue of RSUs' coordination using beacons, and discusses the vehicle slot choice for the initial broadcast of safety-critical messages, in order to guarantee that they are timely delivered.

Year: 2016

Title: Chapter 5, *Medium Access Control (MAC) Techniques for Safety Improvement*

Authors: Nuno Ferreira, José Fonseca.

Book: *Intelligent Transportation Systems: Dependable Vehicular Communications for Improved Road Safety*, Muhammad Alam, Joaquim Ferreira, José Fonseca (Eds.)

ISBN: 978-3-319-28183-4.

Publisher: Springer International Publishing

http://www.springer.com/gb/book/9783319281810