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THÈME

Elaboration d'un mécanisme d'accès au canal pour les applications de sécurité routière des VANETs

Development of new Medium Access Control for VANET road safety applications

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بِسْمِ اللَّهِ الرَّحْمَنِ الرَّحِيمِ

Dedication

*I would like to dedicate this work to my mother
and to the memory of my father
and to my brothers and my wife
and to my son Salmane*

Acknowledgments

Praise be to Allah who helped me to complete my PhD thesis. It has been a very long journey for me as I faced many obstacles and difficulties, and Allah is the only one who gave me the strength and will to continue until the day I defend my dissertation.

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Lakhdar Kamel Ouladdjedid, October 2021

Abstract

The road safety is the main motivation behind inter-vehicular communications under **Vehicular Ad-hoc NETwork (VANET)**. The IEEE 802.11p is the leading standard for **VANET** which adopted the CSMA as a contention-based MAC technique due to its simplicity, dynamicity, as well as its asynchronicity. However, CSMA is always facing a serious problem called “start-of-interval contention” where there is a very high probability that several contender transmitting vehicle are located close to each other after switching to the **Control Channel (CCH)** specially when the network is dense. The collision avoidance mechanism used are not enough to prevent the vehicles from accessing the channel at the same time so that sever transmission collisions will be happening. The CSMA algorithm is so unpredictable, unfair and scales poorly for broadcasted beacons. in the other hand, the **Time Division Multiple Access (TDMA)** medium access mechanism is an excellent candidate for use in VANETs among existing contention-free MAC techniques. It outperforms CSMA and fulfils the complex communication requirements of the traffic safety applications. However, the price paid for the superior performance of TDMA is the required network synchronization through heavy network control overhead.

The focus of this thesis is to investigate the medium access control methods, when used for beaconing protocol over **VANET**. The first proposal of the thesis is called **Carrier Sense for Slotted-ALOHA random multiple access MAC (CSSA MAC)**. It can be seamlessly integrated on top of the IEEE 802.11p standard. . The second contribution of the thesis is the design of an in-band signalization to enhance the **TDMA** method. It is called **CSma with TDms MAC (CSTD MAC)** which aims to ensure a good allocation slots with less network overhead. The conducted simulations show that the proposed schemes give a good performance, in respect to safety application requirements, compared to existing protocols of the same category.

Keywords: VANET, medium access control, CSMA, 802.11p, TDMA, Beaconing, CSSA MAC, CSTD MAC.

La sécurité routière est la principale motivation derrière les communications intervéhiculaires sous les réseaux ad hoc véhiculaires (VANET). L'IEEE 802.11p est la principale norme pour les VANETs qui ont adopté le Carrier Sense Multiple Access (CSMA) comme technique MAC basée sur la contention en raison de sa simplicité, de sa dynamique ainsi que de son asynchronisme. Cependant, le CSMA est toujours confronté à un problème sérieux appelé "conflit de début d'intervalle" où il existe une très forte probabilité que plusieurs véhicules émetteurs concurrents soient situés à proximité les uns des autres après le basculement vers le CCH, en particulier lorsque le réseau est dense. Les mécanismes de résolution de collision ne sont pas suffisants pour empêcher les véhicules d'accéder au canal en même temps, de sorte que de graves collisions de transmission se produisent. L'algorithme CSMA est tellement imprévisible et injuste, en plus d'être mal dimensionné pour les balises diffusées. Le mécanisme d'accès au support à accès multiple par répartition dans le temps (TDMA) est un excellent candidat pour une utilisation dans les VANETs parmi les techniques MAC sans contention existantes. Il peut surpasser le CSMA et assurer les exigences de communication complexes des applications de sécurité routière. Cependant, le prix à payer pour les performances supérieures de le TDMA est la synchronisation du réseau requise par le biais d'une lourde charge de contrôle du réseau. L'objectif de cette thèse est d'étudier les méthodes de contrôle d'accès au support, lorsqu'elles sont utilisées pour le protocole de balisage sur les réseaux ad hoc véhiculaires. Le premier protocole proposé de la thèse s'appelle Carrier Sense for Slotted-ALOHA random multiple access MAC (CSSA MAC). Il peut être intégré de manière transparente au-dessus de la norme IEEE 802.11p. Son objectif est d'améliorer le procédé CSMA en empêchant les accès aux canaux simultanés qui se produisent lors du basculement vers le CCH. La deuxième contribution de la thèse est la conception d'une signalisation in-band pour améliorer la méthode TDMA. Elle s'appelle CSma avec TDms MAC (CSTD MAC) qui vise à assurer une bonne allocation des slots avec moins de surcharge réseau.

Les simulations réalisées montrent que les schémas proposés donnent de bonnes performances, en ce qui concerne les exigences d'application de sécurité, par rapport aux protocoles existants de la même catégorie.

Mots clés: VANET, contrôle d'accès au support, CSMA, 802.11p, TDMA, balisage, CSSA MAC, CSTD MAC,

ملخص

السلامة على الطرق هي الدافع الرئيسي وراء الاتصالات بين المركبات في ظل الشبكات المخصصة للمركبات (VANET). يعتبر IEEE 802.11p هو المعيار الرائد لشبكات VANET التي اعتمدت أسلوب الوصول المتعدد للقناة (CSMA) كأسلوب MAC قائم على التنافس نظرًا لبساطته وديناميكيته، ولكن هذه الآلية لا تكفي لمنع المركبات من الوصول إلى القناة في نفس الوقت بحيث تحدث تصادمات نقل متزامنة.

ينصب تركيز هذه الأطروحة على اقتراح طرق جديدة للتحكم في الوصول إلى وسائط نقل المعلومات عند استخدامها لبروتوكول الإشارة عبر الشبكات المخصصة للمركبات (VANETs). يُطلق على الاقتراح الأول للأطروحة اسم Carrier Sense for Slotted-ALOHA MAC عشوائي متعدد الوصول (CSSA MAC). يمكن دمجه بسلسلة فوق معيار IEEE 802.11p. والهدف منه هو تعزيز طريقة CSMA من خلال منع عمليات الوصول المتزامنة للرسائل التي تحدث عند التبديل إلى قناة CCH. المساهمة الثانية للأطروحة هي تصميم إشارة داخل نطاق الرسالة لتعزيز طريقة TDMA، يطلق عليه CSTD MAC وهو اختصار لـ CSma with TDms MAC والذي يهدف إلى ضمان تسيير جيد لطريقة TDMA بتبادل معلومات أقل في الشبكة.

تظهر عمليات المحاكاة التي تم إجراؤها أن المخططات المقترحة تعطي أداءً جيدًا فيما يتعلق بمتطلبات تطبيق السلامة، مقارنة بالبروتوكولات الحالية من نفس الفئة.

الكلمة المفتاحية: VANET, medium access control, CSMA, 802.11p, TDMA, Beaconing, CSSA MAC, CSTD MAC

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List of Acronyms

A | B | C | D | E | F | G | H | I | L | M | O | P | Q | R | S | T | U | V | W

A

ABGR Adaptive Beacon Generation Rate. 73

ACK Acknowledgment. 3

ADBP Average Dropped Beacon Probability. 156

ADHOC-MAC MAC protocol for ad hoc networks. 78

ADR Average Discovery Ratio. 134

AFAR Average Fairness of Access Ratio. 133

AIFS Arbitration Interframe Space. 40

AMACP Average medium access collisions probability. 133

APIT Average Packet Inter-arrival Time. 134

ASDM Adaptive Space-Division Multiplexing. 79

ASMAP Average successful Medium access probability. 133

ASTM American Society for Testing and Materials. 23

ATGR Average Time Gaps Ratio. 134

AvgTGR Average of Time Gaps Ratio. 125

B

BMSF Broadcast Mechanism For Safety Messages. [74](#)

BSA Basic Set of Applications. [11](#)

BSM Basic Safety Message. [1](#), [33](#)

BSS Basic Service Set. [38](#)

C

CAM Cooperative Awareness Message. [1](#), [33](#)

CBA Collision-based Beacon rate Adaptation. [68](#)

CBR Channel Busy Ratio. [44](#), [75](#)

CCA Clear Channel Assessment. [40](#)

CEB Collision-Expiration Back-off. [70](#)

CEN Comité Européen de Standardization. [24](#)

C-ITS Cooperative Intelligent Transport Systems. [1](#), [5](#), [7](#), [9](#), [19](#)

CCH Control Channel. [iii](#), [3](#), [4](#), [28](#)

CS-TDMA Scalable CSMA and Self-Organizing TDMA MAC. [84](#)

CSMA Carrier Sense Multiple Access. [3](#)

CSSA MAC Carrier Sense for Slotted-ALOHA random multiple access MAC. [iii](#), [4](#), [5](#), [6](#), [108](#)

CSTD MAC CSma with TDms MAC. [iii](#), [5](#), [6](#), [92](#)

CTMAC Cooperative TDMA MAC. [86](#)

CW Contention Window. [3](#), [40](#)

D

DCAM Distributed channel access mechanisms. [38](#)

DCAP Density-based Congestion Avoidance Protocol. [74](#)

DCC Distributed Congestion Control. [5](#), [38](#), [43](#)

DCF Distributed Coordination Function. [39](#)

DCW Dynamic Contention Window. [65](#)

DENM Decentralized Environmental Notification Message. [1](#), [33](#)

DSRC Dedicated Short Range Communications. [8](#)

DTB-MAC Dynamic Token-Based MAC protocol. [71](#)

E

ECC Electronic Communication Committee. [28](#)

EDCA Enhanced Distributed Channel Access. [39](#)

EEBL Emergency Electronic Brake Lights. [11](#), [14](#)

EFC Electronic Fee Collection. [11](#)

ETSI TC ITS European Telecommunications Standards Institute Technical Committee Intelligent Transport Systems. [11](#)

E-UTRAN Evolved-Universal Terrestrial Radio Access Network. [10](#)

EDGE Enhanced Data Rates for GSM Evolution. [10](#)

ETC Electronic Toll Collection. [8](#)

F

FCC Federal Communications Commission. [28](#)

FI Frame Information. [63](#)

FLB Fuzzy Logic-based Broadcast MAC Controller. [64](#)

FM Frequency Modulation. [8](#)

G

GLOSA Green Light Optimal Speed Assistant. [12](#)

GPRS General Packet Radio Service. [10](#)

GSM Global System for Mobile Communication. [10](#)

H

HER-MAC Hybrid Efficient and Reliable MAC for vehicular ad hoc networks HER-MAC. 83

I

IBSS Independent BSS. 38

IRCW Intersection Risk Collision Warning. 11

IVHS Intelligent Vehicle-Highway Systems. 8

IVI In Vehicle Information. 34

L

LCRW Longitudinal Collision Risk Warning. 14

LIMERIC LLinear Message Rate Integrated Control. 71

LTE Long Term Evolution. 10

M

MAC Medium Access Control. 2

MANET Mobile Ad-hoc NETwork. 9

MAP Map Data. 34

MBA Modified Backoff Algorithm. 66

MCA Multi Channel Access. 38

MoMAC Mobility-aware TDMA MAC. 88

MS-Aloha Mobile Slotted Aloha for Vanets. 81

O

OBU On Board Unit. 27

OCB Outside the Context of the BSS. 39

OHN One-Hop Neighbours. 148

P

PDR Packet Delivery Ratio. [133](#)

PoIN Transport Protocol Experts Group. [13](#)

PPCA Periodic Phase Changing Application. [64](#)

PTS Position-based Transmission time Spreading. [69](#)

Q

QoS Quality of Service. [2](#)

R

RB Reverse Back-off. [65](#)

RBDS Radio Broadcast Data System. [8](#)

RBRC Risk-based Beacon Rate Control Protocol. [73](#)

RDS Radio Data System. [8](#)

RES Random Epoch Selection. [68](#)

RHS Hazard Signaling. [14](#)

ROI Region of Interest. [56](#)

RPC Rate-Power Control. [72](#)

RSU Road Side Unit. [12](#), [27](#)

RTOB Reliable TDMA-based One-hop Broadcast. [85](#)

S

SAE Society for Auto- motive Engineers. [24](#)

SBB Speed-Based-Backoff. [67](#)

SCH Service Channel. [3](#), [4](#), [28](#)

SCMACV Scalable and Cooperative MAC protocol for control channel access in VANETs. [87](#), [90](#)

SDO Standards Development Organizations. [23](#), [24](#)

SPAT Signal Phase and Timing. [34](#)

SPMA Switching Priority algorithm for Medium Access. [70](#)

STDMA Self-organizing Time Division Multiple Access. [82](#)

STT Start of Transmission Time. [4](#), [166](#)

SW Spreading Window. [4](#), [166](#)

T

TDC Transmit Data Rate Control. [45](#)

TDMA Time Division Multiple Access. [iii](#)

THCSO THC.SpaceOccupancy. [132](#)

ThHN Three-Hop Neighbors. [149](#)

THN Two-Hop Neighbors. [148](#)

TIRI Traffic and Recommended Itinerary. [12](#)

TPC Transmit Power Control. [45](#)

TPEG Transport Protocol Experts Group. [13](#)

TRC Transmit Rate Control. [45](#)

TTC Time-to-Collision Classification. [13](#)

U

UMTS Universal Mobile Telecommunication Systems. [10](#)

V

V2D Vehicle-to-Devise. [19](#), [20](#)

V2I Vehicle-to-Infrastructure. [7](#), [8](#), [9](#), [20](#)

V2N Vehicle-to-Network. [19](#)

V2P Vehicle-to-pedestrians. [20](#)

V2V Vehicle-to-Vehicle. [9](#), [20](#)

V2X Vehicle-to-Any. [7](#), [9](#), [19](#)

VAB VANET Adaptive Beaconing based on fuzzy Logic. [72](#)

VANET Vehicular Ad-hoc NETwork. [iii](#), [1](#), [7](#), [9](#)

VeSOMAC Vehicular Self-Organizing MAC. [80](#)

W

WAVE Wireless Access in Vehicular Environments. [3](#), [107](#)

WSMP WAVE Short Message Protocol. [30](#)

General Introduction

Contents

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1.1 Motivation

VANET becomes a part of a larger system called [Cooperative Intelligent Transport Systems \(C-ITS\)](#) [6] where many elements are involved together in addition to vehicles: remote service centers, pedestrians, smart devices, etc. This field received a great deal of attention throughout the world during the last two decades (see **Chapter (2)** **.Section (2)**). C-ITS applications can roughly be categorized into road traffic safety, road traffic efficiency and value added Services. Depending on application, there are mainly two wireless technologies considered for C-ITS; the short-range communication technology IEEE 802.11p which offers the ability for direct communication between ITS stations [7] and cellular networks such as 4G/5G/LTE which depends on a centralized network topology. Road Traffic safety applications are intended to be supported by 802.11p technology. Whereas Road traffic efficiency Applications and value-added services can use both technologies together with the network protocol IPv6 supporting Internet connections (see **Chapter (2)** **. Section (3)**).

Safety-related applications have been considered as the most critical in C-ITS [2] . Standardization activities specify two types of messages to support this category of applications. The first one is the time-triggered position message or beacon message called [Cooperative Awareness Message \(CAM\)](#) in Europe [8] and basic [Basic Safety Message \(BSM\)](#) in the USA [9]. The second one is the event driven message is called [Decentralized Environmental Notification Message](#)

(DENM) in Europe [10], whereas in USA it is referred to as BSM type 2. CAM/BSM packets should be transmitted by each vehicle, with a frequency typically ranging from 1 to 10Hz, allowing it to share its position, speed, and direction with its neighbors. DENM messages, generated when dangerous situations occur, should be transmitted within their lifetime, which is usually limited to 500 ms (see **Chapter (3). Section (3.3)**).

The **Medium Access Control (MAC)** layer is responsible for controlling the access to the communication medium and it plays a fundamental role in the use of the channel and on the performance of the safety applications. The type of MAC method to be used in a particular communication network is selected based on network topology and application (see **Chapter (3). Section (4)**).

Traffic safety applications are different from the majority of existing applications using vehicular communications that is because they require a high reliability and a predictable delay concurrently. the predictable delay means that a message needs to be delivered to the receiver before a predefined deadline, and so falls within the realm of real-time communications. They require high reliability because it is critical for a message to be correctly received by its intended recipient.

The ability to self-organize and scalability are key concepts of the MAC method which operates in an ad hoc topology. The ability of the MAC method to self-organize is highly required since no centralized coordination for the medium access is used in VANETs.

Scalability means that these requirements have to be maintained for varying network density even under a high density of vehicles, since, in VANETs the number of participating vehicles is impossible to predict beforehand.

Moreover, the fairness of sending in the channel for all vehicles need to be guaranteed in order to make them visible to each other. Fairness is the equal probability to access the channel for the same type of data traffic. It represents the same **Quality of Service (QoS)** class in term of channel access for the ITS-stations in the system.

In fact, In a C-ITS operating in a VANET context, the MAC becomes decisive in terms of application performance and achieving good channel utilization. Therefore, the requirements on the MAC method Stem from the following needs: predictability, reliability, scalability, self-organizing and fairness of access to the channel.

1.2 Problem statement

In VANET, vehicles share the same frequency channels, and so it is necessary to control the medium access to prevent the simultaneous transmission between the vehicles located within a same collision area. The collision area of a vehicle can be defined as the radio range covering

its 1-hop and 2-hop neighbors, which causes the known direct and hidden collision problems, respectively [11] (see **Chapter (3). Section (4.1)**).

A VANET constitutes a particularly challenging communication environment due to the rapidly changing station density. Further, the number of participating stations in a VANET is not always known and, more importantly, cannot be restricted. Since the decentralized network topology contains no AP or BS regulating access to the shared channel, scalability issues become more prominent.

The **Carrier Sense Multiple Access (CSMA)** of the IEEE 802.11p standard [12] is a widely adopted contention-based MAC technique in VANETs due to its simplicity, dynamicity, as well as its asynchronicity. The MAC of IEEE 802.11 is a stop-and-wait protocol that uses Request To Send/Clear To Send (RTS/CTS) messages to avoid the hidden collision problem, in addition to keeping the sender waiting for an **Acknowledgment (ACK)** to ensure reliability. If no ACK is returned, a retransmission is allowed by doubling the **Contention Window (CW)** following each unsuccessful attempt (up to CW_{max}), until reaching the maximum number of retransmissions, or until a successful transmission takes place.

The majority of the data transmitted in VANET which support traffic safety Applications will be broadcasted (one-to-many communication) And if every receiver sent an ACK the communication channel would be flooded and lot of collisions will be happened.

However, in a broadcast situation, only one transmission attempt is made, and none of the CSMA mechanisms listed above is used. In fact, the only collision resolution mechanism adopted is the backoff algorithm that introduces small random delays before the transmission. The limited range of discrete random numbers to choose from in the backoff procedure increases the risk of collisions when several contending vehicles are within radio range of each other, and attempt to transmit at the same time. This problem becomes more severe in heavily loaded networks, which cause scalability and reliability problems since the collision is not controlled, and any hidden nodes are not avoidable through the backoff mechanism [13].

The **CCH** is the typical frequency channel where the beacons are sent, so that every vehicle as to follow the data traffic in this specific channel. Of course, other communication channels are typically available to be used in a VANET, termed **Service Channel (SCH)**. The announcement of services on these channels is done through the common control channel. Therefore, all vehicles have to access the control channel periodically, to listen for new messages. In north America, the **Wireless Access in Vehicular Environments (WAVE)** architecture uses the IEEE 802.11p/1609.4 for the MAC layer implementation [14],[15]. It allows the WAVE architecture to run on multiple physical channels using the channel switching mechanism. Such a switching between different channels happens at a frame level. Specifically, this mechanism is addressed by the IEEE

1609.4 standard. Allocating two transmission intervals enables two channels, one for CCH and the other one for SCH. So, right after switching from SCH to CCH, many WAVE devices may simultaneously start the channel access contention period [16]. This “start-of-interval contention” situation results in a high collision risk, especially when the network is dense, as the back-off mechanism, which is executed right after the guard interval, is not enough to prevent the vehicles from accessing the channel at the same time. Thus, when attempting to support real-time applications under dynamic topologies, requiring high communication reliability and low latency, the current MAC layer functioning can be considered a serious problem.

Last but not least, due to the periodic nature of CAM/BSM, all the vehicles will start broadcasting when switched on and, since then, they will keep the generation of messages with the same initial phase. Therefore, if the transmissions of two vehicles collide once, they are likely to collide again and again. Obviously, the situation will be complicated as the density of vehicle increases: the more the vehicles, the more likely the collisions are severe.

1.3 Contributions

The focus of this thesis is to study MAC methods for VANET to support the communication requirements of the safety applications found within C-ITS, by respecting the parameters and constraints arising from C-ITS standardization. Therefore, the major contributions of this thesis are:

- An up to date and the comprehensive survey of the main approaches in the literature that have been proposed to solve the MAC layer congestion issues over vehicular networks. They can be categorized on two main approaches. The Asynchronous CSMA/CA– Based MACs (the Contention-based MAC) and the Synchronous Time-Slotted-based MACs (the contention-free MAC) techniques also known as TDMA-like MAC which has been recently proposed as an alternative to the IEEE 802.11p standard. Besides they are classified according to the transmission parameters of each access mode. Throughout, the benefits and drawbacks of the two categories are discussed which have been considered carefully when developing a MAC methods for traffic safety applications. Combining the advantages of both mechanisms and enhancing them is the goal of the thesis proposal.
- A novel scalable random access MAC for vehicular networks called **CSSA MAC** [17]. It can be seamlessly integrated with IEEE 1609.4 on top of the IEEE 802.11p standard. The objective is to prevent the simultaneous channel accesses which occur upon switching to the CCH. Its main idea is to spread the **Start of Transmission Time (STT)** of the contending vehicles over a **Spreading Window (SW)** during the CCH period. After reaching the STT,

all the vehicles need to back-off for a random period before accessing the channel. The proposed protocol aims to provide an efficient one-hop broadcast access on the CCH, and attempts to minimize the risk of direct and hidden collision problems. A mathematical analysis is made in order to calculate the optimal SW size according to the number of contending vehicles. Using that mathematical model, we show that it is possible to predict the ratio of contention, the probability of collisions, and the wasted time between the first and the last successful transmission. Also, experiments using network simulation show that **CSSA MAC** achieves good performance levels when compared with IEEE 802.11p standard and some other famous protocols. The comparison is done according to seven important performance metrics used for evaluating the MAC methods.

- a new TDMA-based MAC protocol is proposed to achieve better performances in terms of channel access control in VANets when compared to CSMA of the IEEE 802.11p. One of the TDMA challenging schemes is the difficulty to allocate time slots appropriately to the contending vehicles in a distributive manner. Some solutions have been proposed, as AD-HOC MAC [18] and VeSOMAC [19], however, they often result in heavy network control overhead, where they require that the vehicles have to exchange their frame information or list of neighbors. The contribution of this paper includes the design of an in-band signalization, called **CSTD MAC** aiming to ensure a good allocation slots with less network overhead [20]. The conducted primary simulations show that the proposed scheme performs better than CSMA of the IEEE 802.11p by reducing the rate of transmission collision.

1.4 Outline

The remainder of this thesis is organized as follows:

1. **Chapter 2: C-ITS:** This chapter gives an overview of the C-ITS and its applications which are classified based on their impact on the road traffic. Moreover, the requirements of these applications are discussed, especially those regarding traffic safety, as well as the suitable technologies for each category.
2. **Chapter 3: Standardization of C-ITS :** This chapter presents the standardization organizations and their standards. It also, gives a study of the principle of channel access (MAC) in C-ITS, as well as the **Distributed Congestion Control (DCC)** distributed channel management techniques with the existing evaluation methods.
3. **Chapter 4: Literature review of MAC techniques:** This chapter provides an overview

of some related works found in the literature regarding MAC layer solutions. They are categorized in two main classes: contention-based methods represented by CSMA-like protocols and contention-free methods represented by TDMA-like protocols. Discussion is made to extract the benefits and the drawbacks which are all considered carefully in the developing of the thesis proposal regarding traffic safety applications.

4. **Chapter 5: CSSA MAC: The Carrier Sense for Slotted-ALOHA Random Multiple Access MAC:** This chapter introduces the proposed contention-based MAC technique for VANets networks which is called **CSSA MAC**. The chapter starts by showing the principle of the proposal and then provides its analytical foundations in order to justify their parameters and prove their efficiency. In this chapter a simulation study is presented through a network simulator to confirm the analytic finding and to evaluate the performance of CSSA MAC as compared with some famous MAC protocols. The results show a good performance of the proposal and prove its ability to ensure a best trade-off between reducing beacons transmission contention and reducing the time gabs in the channel.
5. **Chapter 6: CSTD-MAC: CSMA with TDMA-like operation for VANET MAC :** The contribution of this chapter includes the design of an in-band signalization, called **CSTD MAC** aiming to ensure a good allocation slots with less network overhead. The conducted initial simulations show that the proposed scheme performs better than CSMA of the IEEE 802.11p by reducing the rate of transmission collision. The chapter starts by showing the principle of the proposal and then provides the simulation work and the performances of the proposed protocol. Finally, it gives a conclude and discusses future works
6. **Chapter 7: general conclusion :** This chapter summarizes the contributions of the thesis and presents a discussion of possible research directions that are still open at the end of this study.

Cooperative Intelligent Transportation System

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2.1 Introduction

Vehicular networks supported by wireless communication, have become one of the key research areas in the wireless networking community. This chapter presents more clearly the context of this thesis by giving an overview of the C-ITS where the Vehicle communication represents the most important part. Section 2.2 provides a short historical description of the evolution of the technologies enabling a vehicle to communicate with other vehicles and the surrounding environment and become part of an extended C-ITS. The evolution from the **Vehicle-to-Infrastructure (V2I)** toward the **Vehicle-to-Any (V2X)** scenarios is discussed as an extension of the original **VANET** concept. In Section 2.3, vehicular applications are classified based on their impact on the road traffic, and the requirements of each category of services are discussed, especially those regarding traffic safety, as well as the suitable technologies. Finally, a conclusion is presented in the Section 2.4.

2.2 History

Improving the road safety using the radio communication, as transmission media, between vehicles has been used well before the digital radio communications that we know today. One

of the attempts is the patent Radio Warning Systems issued on 1925 [1], Figure 2.1. It is based on the peer-to-peer communication concept which connect two devices installed one different vehicles but not yet a wireless network technology as we are familiar with in nowadays.

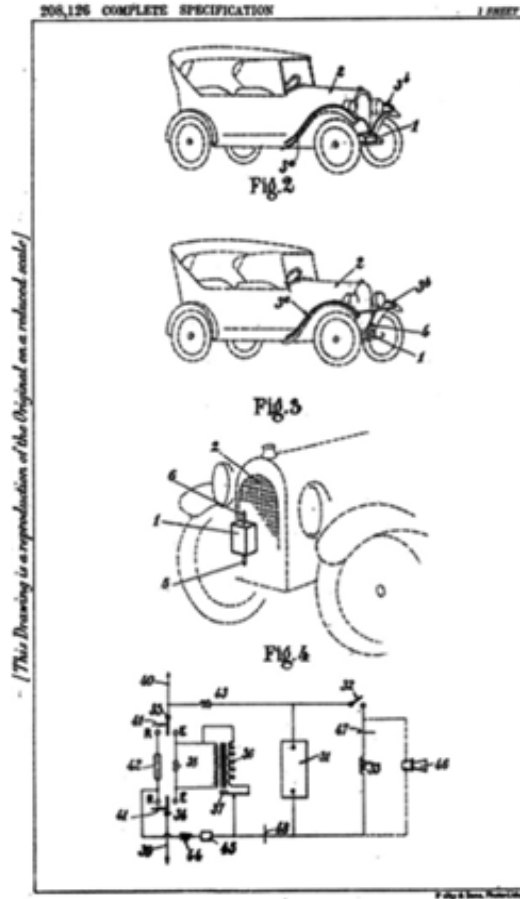


Figure 2.1: Radio Warning Systems for use on Vehicles [1].

The first digital **V2I** communication, proposed in 1980, is called **Radio Data System (RDS)**. It is a communication protocol standard for embedding small amounts of digital information in conventional **Frequency Modulation (FM)** radio broadcasts. A few years later, it was introduced in the USA as **Radio Broadcast Data System (RBDS)** and it became a European standard in 1990. In 2005, RDS was improved to provide RDS-Traffic Message Channel (TMC). Each message contains an event code, location code, expected incident duration, affected extent and other details. However, these communications technologies remained unidirectional. In the early 1990s, Philips has invented the 5.8 GHz **Dedicated Short Range Communications (DSRC)** system an adaptation of 2.45 GHz system, would become the basis for what was then called **Intelligent Vehicle-Highway Systems (IVHS)** communications. It is an application specific vehicular communication systems able to make different types of transactions, as **Electronic Toll Collection (ETC)**, traffic traveller information, automatic vehicle identification etc., and the concept of an

infrastructure controlled “Network” evolved. In this architecture, a network of beacons, operating at 500 kbit/s / 250 kbit/s, would hold short communications sessions with vehicles as they passed within the short (2.5–10 m) range of the beacons. The term DSRC since the 80s has referred to a type of RFID system in Europe and Japan, whereas in the US it refers to a type of WLAN system. The communication technology is intended for hotspots without networking (i.e., single hop where no routing is necessary) and the transmission takes place between vehicles and roadside units (i.e., transponders and readers). However, the vehicles did not communicate with each other so there was not a vehicle network, and the technology was infrastructure driven in a master–slave architecture. On the other hand, the bandwidth was too limited, and the range was too short. In the beginning of 90s, the research activities on vehicular communications have been started, especially, in Germany, after the efforts made in the projects PROMETHEUS and PREVENT [21]. The concept of VANET [2] has appeared, which can be described the vehicular network as “a special case of Mobile Ad-hoc NETWORK (MANET) [22]. VANETs are characterized by the fact that the nodes (vehicles) are changing their density and position rapidly, and as a result, the network topology also changes. Since the term “ad-hoc networking” refers to a network without infrastructure and the network is operating in a peer-to-peer fashion. In the road there is usually heavy density of vehicles and always there are connections between them within their communication range. Following this logic, the researchers have been debated about the need for infrastructure investment, the information messages can be “multi-hopped” to other vehicles in the network using only Vehicle-to-Vehicle (V2V) communication. However, if the car manufacturers agree to equip vehicles with V2V communication capability, the market penetration of these technologies will have to increase gradually. As a result, several decades will be needed before an acceptable level of V2V technology use. For that, it was soon realized that the V2V communication technology alone was not enough to enable a fast and effective deployment of most of the application scenarios proposed by the ITS community and pushed by the policy makers. So, the extension of the same communications principles consists that the vehicle should not restrict its capability to communicate to other vehicle. It should become able to communicate with nodes that can be deployed or used in the road-side infrastructure, so the concept of V2I has been involved in the VANET concept.

After that, more general extension has been proposed under the concept of the V2X. It is a very general term that includes all possible forms of communication involving the external environment. Therefore, the vehicle becomes part of a larger system called Intelligent Transport Systems (ITS) where many elements are involved together: remote service centres, pedestrians, smart devices, etc. Therefore, the terminology C-ITS [1] communications magnifies the benefits offered by autonomous ITS, and leads to greater transport efficiency and increased safety. This

vision is shown in Figure 2.2 representing the vehicle as one of the elements of a large integrated ITS communication ecosystem.

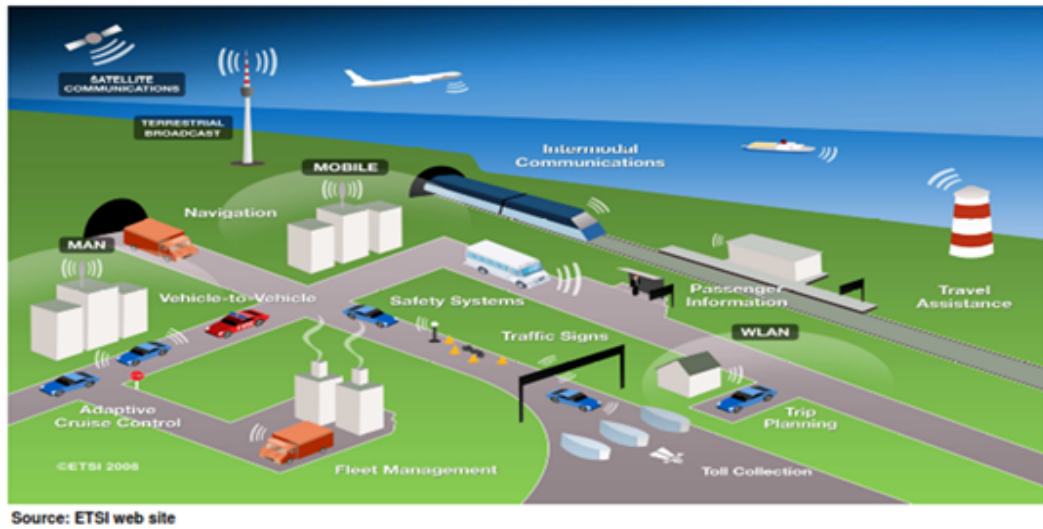


Figure 2.2: The extended ITS scenario (source ETSI ITS) [2]

In fact, the activity around ITS communication has lasted one and half decades and there is not a big significant commercial implementation. There is a gap development between the marketing departments of car manufacturers and their Research departments and this is because of several reasons. One factor was that the car manufacturers were not ready or not see the potential benefits of the communication between vehicles, and another was that the lack of standardization for these future communication systems. But the communication technology evolution moved faster than ITS research and the world of mobile communications had sprinted forward. The cellphones had switched to the second generation networks (2G) which supported digital data as well as voice, presented by [Global System for Mobile Communication \(GSM\)](#) and [Universal Mobile Telecommunication Systems \(UMTS\)](#). After that, they moved to [General Packet Radio Service \(GPRS\)](#) and to [Enhanced Data Rates for GSM Evolution \(EDGE\)](#), with a theoretical transfer speed of max. 250 kbit/s (150 kbit/s in practice), In the beginning of 2012, a new generation networks started to be introduced called 3.9G and 4G. they are fundamentally different from previous generations which are “circuit switched networks”, these systems are “packet switched networks”, capable of rapid and fast evolving data rates, offering peak download rates up to 299.6 Mbit/s and upload rates up to 75.4 Mbit/s. known, as [Evolved-Universal Terrestrial Radio Access Network \(E-UTRAN\)](#), and in Europe as [Long Term Evolution \(LTE\)](#). Nowadays, everyone has a smartphone and the majority of these smartphones support Bluetooth, Wifi, 2G/3G/4G mobile networks. It is now only one step further for the car manufacturers to use these technologies and be embedded in the vehicle for ITS service

provisions. At the writing of this thesis, the actual technology proposed that affect ITS are restricted to three areas [2]: (1) [Electronic Fee Collection \(EFC\)](#), (2) HGV Tachographs which are devices that record information about driving time, speed and distance. This information is used to monitor compliance with drivers' hours rules. However, HGV tachograph remote read and weigh in motion are still future regulations and HGV. (3) eCall which is described as mobile network based on the use of a circuit-switched voice channel to deliver both the data coming from the vehicle involved in a road accident and the actual voice call. Regrettably, the time elapsed since the completion of the standardization work and the decision about the actual operational deployment has took a long time and in the meanwhile the mobile network technology has evolved introducing different technologies (3G/4G/5G).

2.3 Applications and Technology specifications

2.3.1 Application Categories

C-ITS communications are originally proposed to decrease the number of traffic accidents by introducing traffic safety applications, but also to reduce congestion, travel-time and pollution. In 2008, a Basic Set of Applications (BSA) [Basic Set of Applications \(BSA\)](#) has defined by ETSI TC ITS [European Telecommunications Standards Institute Technical Committee Intelligent Transport Systems \(ETSI TC ITS\)](#) [23], that may be supported by C-ITS technologies for "day one deployment". Three classes of applications have been proposed to this effect, targeting safety, traffic efficiency and added-value services [24]. In the part, these applications are discussed with showing the important characteristics and meaningful use-cases [24].

2.3.1.1 Safety

Safety applications are the first motivation behind inter-vehicular communications. They aim at reducing the risk of car accidents and protect vehicle occupants and pedestrians lives. A large number of use-cases can be found in this category, with examples as longitudinal collision risk warning, intersection collision risk warning, traffic light violation warning, lane changing warning, but there are two representative safety applications which are able to cover the most of requirements can be met in this category of applications. The first is the [Intersection Risk Collision Warning \(IRCW\)](#) which has the objective to increase the drivers' awareness to avoid collisions at intersection in urban area where low visibility is high at crossroads. It broadcasts periodic status messages, or beacons, containing internal information like geographical location, velocity or acceleration. The second is the [Emergency Electronic Brake Lights \(EEBL\)](#), it targets the chain accident produced by the sudden braking of the vehicle been in critical situation. All the use-cases of this category can be implemented using either beacons or special notification

messages which are explained with more details in Section 2.3.2. Most of the applications in this class are built on direct vehicle-to-vehicle communication, only some use-cases require special infrastructure. It means that the safety application's efficiency depends on the penetration ratio of V2V communication technology.

2.3.1.2 Traffic Efficiency

The goal of traffic efficiency application is to reduce the time spent by the drivers on the road and facilitate the flows of vehicles by avoiding the traffic congestion. The consequence of this optimized behavior is the reduction in fuel consumption and in pollution. The applications of this category do not require a high penetration ratio of V2V communication technologies. They can work using specialized infrastructure for V2I communication or already 3G/4G networks. Due to the expensive cost of the V2I communications infrastructure, the deployment expectation of the traffic efficiency applications will be at first available only in certain zones, then the penetration of direct V2V communications will help increase the coverage area. The traffic efficiency applications are internet web-based services so their delay requirements are more flexible compared to the safety applications. However, their performances gradually degrade with the increase of packet loss and delay. According to the type of information required, the use-cases of this category can be divided into two groups, which can be applied either in local scope or in large and remote area. For example the [Green Light Optimal Speed Assistant \(GLOSA\)](#) is a case where the scope of application is local, with the objective is to adjust the optimal speed to reach the traffic light in a green phase, hence reducing stop time and fuel consumption. In this application the [Road Side Unit \(RSU\)](#) transmit a beacons related to a traffic light cycle to incoming vehicles situated in a range of a few hundred meters. It can be realized by V2I communication or by a hybrid approach where some vehicles could act as relays. On the contrary, the objective of the large scope applications is to gather data from much large areas, in the level of tens or hundreds of kilometers. One of the examples is the [Traffic and Recommended Itinerary \(TIRI\)](#) which meant to be a complement to the current navigation system to help drivers avoiding congestion. The traffic information is collected periodically by vehicles from internal and external sensors is aggregated and then sent to a central authority from entire city using RSUs or Cellular Networks. The central authority process the data in order to predict traffic congestion and send up-to-date global traffic information back to the vehicle's navigation system. Meanwhile, vehicles can request traffic related information from a service provider.

2.3.1.3 Value-add services

This category of application consists of use-cases that can bring an extra-value to the vehicular network without any effect on road traffic. They can be one of two kinds, infotainment or

business As well as the traffic efficiency, the infrastructure plays an important role in this context and they usually are based on Internet web-services which use TCP/IP (transmission control protocol, Internet protocol) for the data transmission. It is known that the web-services are not time critical, based on best-effort traffic patterns with less QoS requirements and responsible only for the successful transmission. The Applications of infotainment aim to facilitate the driver's daily life. They incorporate different classes, the first one is the context-related driver information, such as remote software updates for the vehicle and location-based services. A typical application from this class is the [Transport Protocol Experts Group \(PoIN\)](#) where a vehicle can receive information about places like hotels, restaurants and parking or commercial. The second one is the entertainment related applications class, such as Internet media streaming, video streaming, and information services, web-browsing, social networking, gaming, and access to different cloud services. In this class the data to be transferred is much big than the case with the safety application. On the other hand, the business applications play an important role in the automotive industry. The typical example in this class is the Fleet Management solutions, which could ensure the on demand access to real-time vehicles data like vehicle, position, speed, freight or engine status.

2.3.2 Time-to-Collision Classification

There are many methods to classify the application categories. The famous one is based on [Time-to-Collision Classification \(TTC\)](#) parameter proposed by Hayward [25]. This parameter measures the time required for a collision between two vehicles continue at their speed and on the same path. The BSA applications are classified according to TTC principal as presented in the Figure 2.3 The TTC values illustrated in the figure are only indicative.

The three parts of the TTC classification are presented as follows [2]:

- **Road traffic and telematics** : These services are value-add for enhancing the driving comfort and entertainment. They also may help drivers, at large scale, to adjust the navigation plan and to be informed of road traffic status to improve traffic efficiency and to reduce road traffic pollution. [Transport Protocol Experts Group \(TPEG\)](#) application [26] is an example of road information application. It can deliver various types of content including traffic events and traffic flow and prediction , parking information, fuel price information, and weather information
- **Drinving assistance** : are applications for assisting driver to avoid traffic jam or to pay attention to overcome a potential dangerous situations, the applications of this category can provide the driver by:

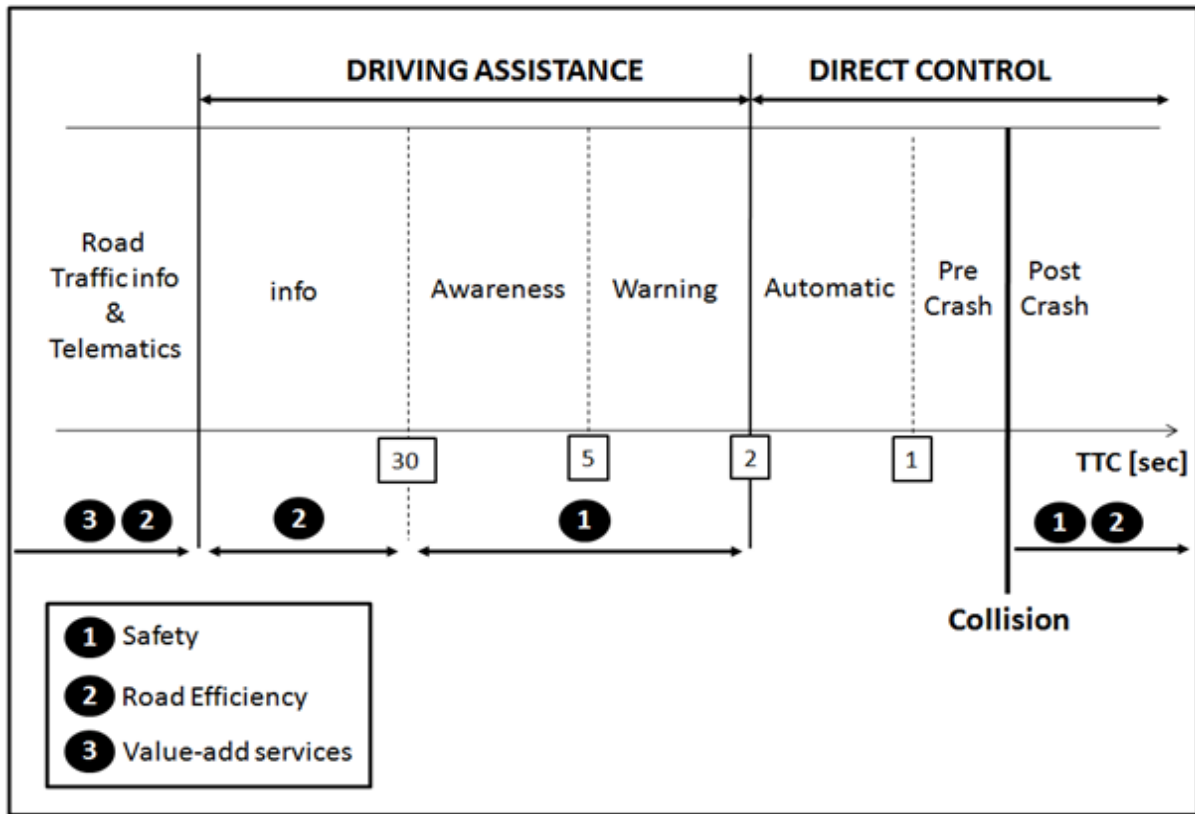


Figure 2.3: Classification of BSA applications based on TTC.

- **An information** as reminder for traffic rules like speed limit or road conditions like traffic jam),
- **An awareness** message after detecting road hazards like a stationary vehicle at road side or hard break vehicle ahead. [Hazard Signaling \(RHS\)](#) application [27] is an example for awareness application.
- **A warning** message to take immediate actions to avoid potential collision. [Longitudinal Collision Risk Warning \(LCRW\)](#) application [28] and [Electronic Emergency Brake Light EEBL](#) application [29] are examples for warning application.

At this stage, there is no automatic control to the in-vehicle systems. Driver keeps the control on the vehicle maneuvering.

- **Direct control**: if the TTC is further reduced and the collision cannot be avoided, this category of applications takes over the control of vehicle and control the system automatically. For that two sub classes of applications can be launched:
 - **The automatic and pre-crash applications** are to minimize the impact of collision and to reduce both human and material damage may happened.

- **Post crash applications** come just after the collision; they consist to enhance the rescue efficiency by accelerating the response of the rescue organizations. One of the applications of this purpose is the eCall system adopted in Europe which is a vehicle emergency call system. In case of road accident, the on-board device will automatically dial 112 and set up voice connection with back-end office [29]. At the same time, the geographical position will be transmitted to the nearest emergency agency through the wireless infrastructure such as 2G/3G to organize the rescue plan. Another application can be launched to support the Emergency vehicle approaching as a continuation of the rescue process. Afterward, one of the road efficient applications will be triggered in this situation which is the route guidance application. It predicts traffic congestion in the accident zone, so it advises drivers to take an alternative route before ending up in queue with no possibility of turning back. It is remarkable that safety and road efficiency applications bind to each other, one can trigger the other.

Currently, the research activities around C-ITS communications focus only on the three parts of the driver assistance category and almost the collision risk warning (2-5 s) window. It represents the first deployment of simple non-complex Day One services where the purpose is to notify the driver and not to take the control over the vehicle (Automatic and Pre-crash window). It is up to the driver to take the last decision and to perform the necessary operation.

In Table 2.1 an overview of the important list of C-ITS application use-cases, the majority of them are proposed by ETSI TC ITS [23] and the others are technologies used currently. The list is organized according to the classification proposed in Figure 2.3.

2.3.3 Application requirements

The C-ITS applications can range from conventional web and email to traffic collision avoidance applications. Mainly three types of applications are considered: traffic safety, traffic efficiency and value-added services. They have different communication requirement and the most import of them are those regarding reliability and delay.

The reliability is coupled with the error probability of packets which should reach its or their intended recipients, but the Delay is the time needed to deliver the message to its or their intended recipient [30]. Data from a video conference can tolerate a lower reliability, it means a higher tolerance for packet loss, but is instead very delay sensitive (predictable) where the delivery has to be sent before predictable deadline. Emailing requires high reliability, and the packets must be received correctly, but it has less stringent delay requirements, i.e., the email needs to be delivered as soon as possible (best effort), which means retransmissions can be used to increase the reliability [4]. In brief, traffic safety applications require that the end receiver has to have sufficient time to react and the both traffic efficiency and value-added services applications require clear delivery to the end receiver [11]. The table 2.2 resumes the QoS, in term of reliability and delay, required by the typical uses-cases of the C-ITS applications.

Table 2.1: C-ITS application use-cases

Category		Application use-cases
Safety	Drinving assistance (Warning)	• Longitudinal collision risk warning, • Intersection collision risk warning, • Emergency electronic brake light, • Traffic light violation warning, • Lane change warning,
	Drinving assistance (Awareness)	• Cooperative awareness, • Slow vehicle, • Stationary vehicle, • Wrong way driving, • Adverse weather condition, • Hazardous location, • Traffic condition, • Road work, • And human presence,
	Direct control (Post-crash)	• Vehicle emergency call system (eCall), • Emergency vehicle approaching,
Road efficiency	Drinving assistance (Info)	• Vehicle emergency call system (eCall), • Emergency vehicle approaching,
	Direct control (Post-crash)	• Accident announcement and congestion prediction,
	Road traffic and telematics	• Traffic and Recommended Itinerary prediction, • Traffic events, • Navigation plan,

Value add-service	Road traffic and telematics	• Remote software updates for the vehicle, • Point of Interest Notification (like hotels, restaurants and parking or commercial), • Fleet Management, • Fuel price information, • Weather information, • Entertainment related applications such as Internet media streaming, video streaming, web-browsing, social networking, gaming.,
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Table 2.2: ITS applications requirements

		Reliability		Delay	
		low	High	Best effort	Predictable
Safety	Intersection Risk Collision Warning		X		X
	Emergency Electronic Brake Lights		X		X
Traffic Efficiency	Green Light Optimal Speed Assistant		X	X	
	Traffic and Recommended Itinerary		X	X	
Value-add services	Point of Interest Notification		X	X	
	e-mail		X	X	
	web-browsing	X		X	
	Fleet Management		X	X	

Some characteristics of C-ITS applications have to be taken in account for the development of specific technologies. As mentioned in the Table 2.3. The traffic pattern represents the way how the information packets are generated. For the safety application the traffic is generated either periodically or as reaction to an external event using special type of messages, whereas in the other applications, the traffic is generated after the demand of the driver and exchanged through the internet protocols.

The second characteristic of C-ITS applications is The communication mode which represents the way of dissemination, it can be broadcast, unicast or geocast. The information generated by

safety applications is perishable with short life-time due to the movement of vehicles, the higher speed of the vehicle the shorter time of communication is allotted.

For that reason the communication mode of the majority of safety applications require an easy dissemination of information locally around the vehicles, built on direct V2V broadcast communication where no detour around an access point (AP) is necessary. The other C-ITS applications do not relay on short delay requirements and use information needs to be spread regionally rather than locally using unicast or geocast with both V2I and V2V communication. While the communication range defines the area of interest; some applications require short transmission beyond one-hop communication range, thus requiring medium or long via multi-hop communication range.

Table 2.3: Table to test captions and labels.

	Traffic patern	Communication range	Communication mode
Safety	Periodic /Event-based message	Short and Medium (Onehop/MultiHop)	generally V2V Broadcast (Onehop/MultiHop)
Traffic Efficiency	Driver and internet – based traffic	Medium and Long (MultiHop)	Unicast/geocast V2V/V2I
Value-add services	Driver and internet – based traffic	Long (MultiHop)	Unicast/geocast V2V/V2I

2.3.4 The needed Technologies

The need for dedicated technologies to satisfy the operational requirements of C-ITS applications is well understood. The research community has investigated the existing communication technologies to decide which is the most appropriate for vehicular communications. The researchers have described the specification of the needed technologies for the application having stringent requirements on both delay and reliability like safety critical applications. They have to sit with the technology developers to work on a practicable solution.

Starting from the concept of V2X network which is the term that includes all possible forms of communication where Vehicles can communicate with all the elements involved in the ITS system. The V2X network can offer to vehicles two kinds of communication, one is the Direct Vehicle-to-Devis (V2D) communication and the second is the Vehicle-to-Network (V2N) communication. V2D is to establish a direct local link between vehicles and their environment; it

can be between vehicles and each other (V2V), vehicles and road side units exchanging information for safety purposes (V2I) and vehicles with vulnerable road users, such as pedestrians and cyclists using mobile device like Smartphone or a table (Vehicle-to-pedestrians (V2P)). V2D offers a hope gain rather than two hopes when passing through cellular infrastructure which gives further reduction of latencies in local data exchanging at high terminal speeds [31], [32]. V2D communication is suitable for safety critical applications requiring bounded delay and high reliability, it can address all of road safety applications and as well improve the traffic efficiency (see Figure 2.4).

DSRC (Dedicated Short-Range Communications), known as G5-ITS in Europe, is the name of wireless communication technology standardized to provide a key foundation for V2D communications. It has the ability to enable connectivity for high mobility and high speeds until 500 km/h, even in presence of obstructions, in communication range over 1Km [33]. A dedicated transmission spectrum at 5 GHz band was allocated for DSRC to initiate the deployment of V2D technologies. Protocol stacks dedicated for supporting DSRC have been developed in the USA and in Europe (WAVE and ETSI, see Chapter 3, Section 3). The 802.11p standard is the common denominator of these protocol stacks which supports MAC/PHY layers (see Chapter 3, Section 4) for V2D communications.

Road traffic efficiency Applications and value-added services can use direct V2D technologies. However, due to the low density with a lot of fragmentation especially in the off-peak hours, the V2V communications cannot be supported. Moreover, the expensive cost of specialized infrastructure for V2I communication, the first deployment of the traffic efficiency applications will be available only in certain zones.

Whereas, the use of V2N represent a viable solution to extend connectivity in those cases for these applications since they are not time critical. The coverage area will be increased by the existing 4G/ 5G LTE networks, since the applications are not time critical. Vehicles can connect to 4G/5G LTE network, retrieve information and services from control centers and act as a provider by transmitting announcement directly to surrounding vehicles using 802.11p (V2D) (see Figure 2.5).

A hybrid communication approach in which both technologies work together is the best way to support C-ITS applications [34]:

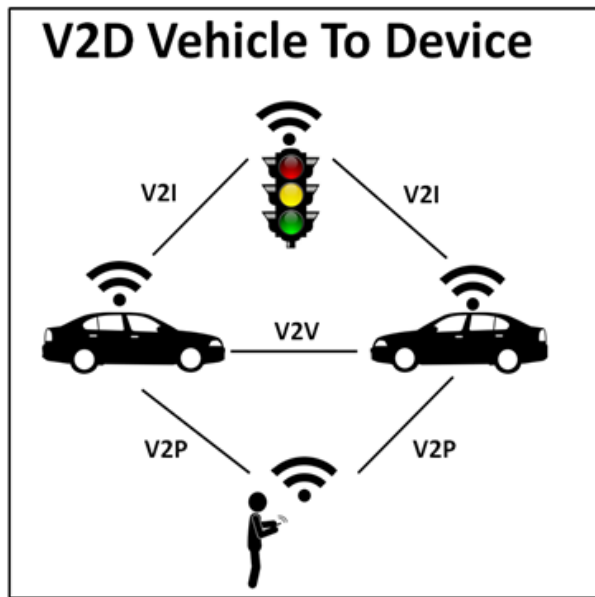


Figure 2.4: Direct communication using DSRC for V2X operation at ITS band (5.9 GHz).



Figure 2.5: Network communication using 3G/ 4G LTE for V2N operation in licensed cellular band.

1. DSRC (G5-ITS) delivering safety critical messages at 5.9 GHz band allocate to V2D communications
2. 4G/5G LTE providing information for infrastructure related services using V2N communications at the 3.2-3.8 GHz band allocated to cellular.

2.4 Conclusion

This chapter gives an overview of the most distinctive aspect of the design of C-IVC technologies which is the role of the applications as well as their requirement. Despite of the big activities around C-ITS communications by the researchers of the field during the lasted one and half decades and there is not a big significant commercial implementation and this is because of several raisons. One of them is that the car manufacturers were not ready or not see the potential benefits of the communication between vehicles, specially with the high heterogeneity of the automotive industry where a solution for C-ITS communication can be successful only if it is adopted by all the car manufacturers. However, it is hard to be accepted by them because they usually distinguish themselves from their competitors by proposing proprietary systems. Standardization work is therefore essential in this context in order to ensure the harmonization between the car manufacturers for a global use. the standardization activities have to be completed because it is clear that C-ITS safety systems still requires to be supported by a fast ITS dedicated communication technologies.

Standardization of C-ITS

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3.1 Introduction

The goal of standardization of C-ITS is to allow implementation of communication protocols in interoperable way, such that vehicle from different vendors can speak the same language and exchange messages based on common syntax and semantics. Much has happened during the last decade within all major [Standards Development Organizations \(SDO\)](#) dealing with vehicular communications. In 2003, the [American Society for Testing and Materials \(ASTM\)](#) has proposed a standard by emanating from the WLAN standard IEEE 802.11 and made some minor changes to adapted to the high-speed vehicular environment. The standard made use of a simple mailbox application layer [35] and the resulting protocol stack contained three layers: application, data link and physical. In the same year, IEEE took over the work from ASTM

and they have extended the protocol stack with more layers for supporting safety and non-safety applications which includes the physical layer up to the transport layer. It has been given the name wireless access in vehicular environment (WAVE). In Europe The European Telecommunications Standards Institute Technical Committee Intelligent Transport Systems (ETSI TC ITS) is responsible for developing the whole protocol stack including vehicle-centric road traffic safety applications, whereas applications orienting towards road traffic efficiency utilizing road infrastructure are under the responsibility of The [Comité Européen de Standardization \(CEN\)](#). The [Society for Automotive Engineers \(SAE\)](#) is developing a message set dictionary [9] to be used by road traffic safety applications which is a technology agnostic, i.e., not relying on a particular wireless access technology.

This chapter settles more clearly the context of this thesis by giving an overview of the standardization activities in the field of C-ITS. In Section 3.1, the famous [SDO](#) are presented based on their activities on C-ITS. Section 3.2 contains a description of ongoing standardization efforts to build the C-ITS device, with a focus on the similarities and differences that can be distinguished between the US and European architectures. Finally, Section 3.3 is entirely dedicated to a general review of the Standardized channel Access mechanisms in vehicular networks where the IEEE 802.11p standard is introduced. It presents the tools used for MAC's behavior evaluation which can be ranged from the most practical to the most theoretical as well as the evaluation criteria.

3.2 Standard Development Organization

Different [SDOs](#) have been involved and are active in standardizing the specific communication stacks. The standardization process is achieved with different governmental and non-governmental SDOs, as shown in Figure 3.1.

The most famous governmental SDOs are:

- **ISO/TC 204** : The International Standards Organization (ISO) Technical Committee (TC) 204 “Intelligent Transport Systems.” is created in 1992 with its 18 working groups (WGs). ISO/TC 204 takes into account the existing works of international standardization bodies and build its general system and infrastructure aspects of ITS. Communications access for land mobiles (CALM) is an initiative by members of the ISO TC 204/Working Group



Figure 3.1: Standard Development Organizations developing ITS [3][2].

16 to define a set of wireless communication protocols and air interfaces for a variety of communication scenarios [36].

- **CEN/TC 278** : The Comité Européen de Standardization (CEN) TC 278 ITS is responsible for managing the preparation of standards in the field of Intelligent Transport Systems (ITS) in Europe. CEN/TC 278 ITS is established in 1991 and serves as a Standardisation platform for European stakeholder in the field of telematics to be applied to road traffic and transport [37] [38].
- **ITU** : International Telecommunication Union has tried to propose a unit for ITS, but no standards are declared so far.

The non-government SDOs are:

- **ETSI/TC ITS** : The European Telecommunications Standards Institute (ETSI) is one of the three bodies officially recognized by the EU as a European Standards Organization (ESO). ETSI Technical Committee (TC) Intelligent Transport Systems (ITS) was created in 2007 to benefit from the competence of ETSI center on testing with the objective to carry out the development and maintenance of Standards, to support the implementation of ITS Communications. In practice, ETSI TC ITS followed a vehicle-centred approach focused on a single protocol stack for V2V and V2I communications [39].

- **IEEE** : Institute of Electrical and Electronics Engineers (IEEE) is the world's largest technical professional society promoting the development and application of electrotechnology and allied sciences for the benefit of humanity [40]. IEEE developed standards used to support the ITS, such as IEEE 802.11p and its approved expansion IEEE 1609 known under the work named "Wireless Access in Vehicular Environment" (WAVE) [41] .
- **SAE** : The Society of Automotive Engineers, in the USA, is a complementary organization developing standard-like specification of data dictionaries and referred to as message sets. SAE cooperates with organization standardization.
- **ARIB** : the Association of Radio Industries and Businesses in Japan is a standardization organization investigates research and development on C-ITS.

The C-ITS standardization have a growing interest by the SDOs from around the world. Therefore the integration of different standards into a global C-ITS scenario will have some inconsistency and gaps. This situation motivates the SDOs, involved in the process, to collaborate for an international harmonizations with the aim of reducing costs of deployment and maintenance and allowing a worldwide market. In Europe, the CEN, ISO and ETSI start working jointly in October 2009 together under the European commission's mandate M/453 [42] for an important harmonization activity where the term C-ITS was created in the context of this mandate. CEN/ISO are working on all entities used in the C-ITS protocol stack needed by all stakeholders like vehicle maker, road operators, city authorities, cellular network operators) as shown in Figure 3.2.

The join EU/US harmonization approach is presented by two cooperation activities; one is the link between SAE and CEN/ISO/ETSI together in order to achieve harmonized propositions for message sets directly from the beginning. Second is the Harmonization Task Groups (HTG, with their eight groups) investigates gaps and overlaps of communication and security aspect for already existing standards and also provide recommendation to SDOs on missing standards and standards to be harmonized. As an example the HTG3 published a recommendation to harmonize the message formats of two protocol sets from ISO and IEEE [43].

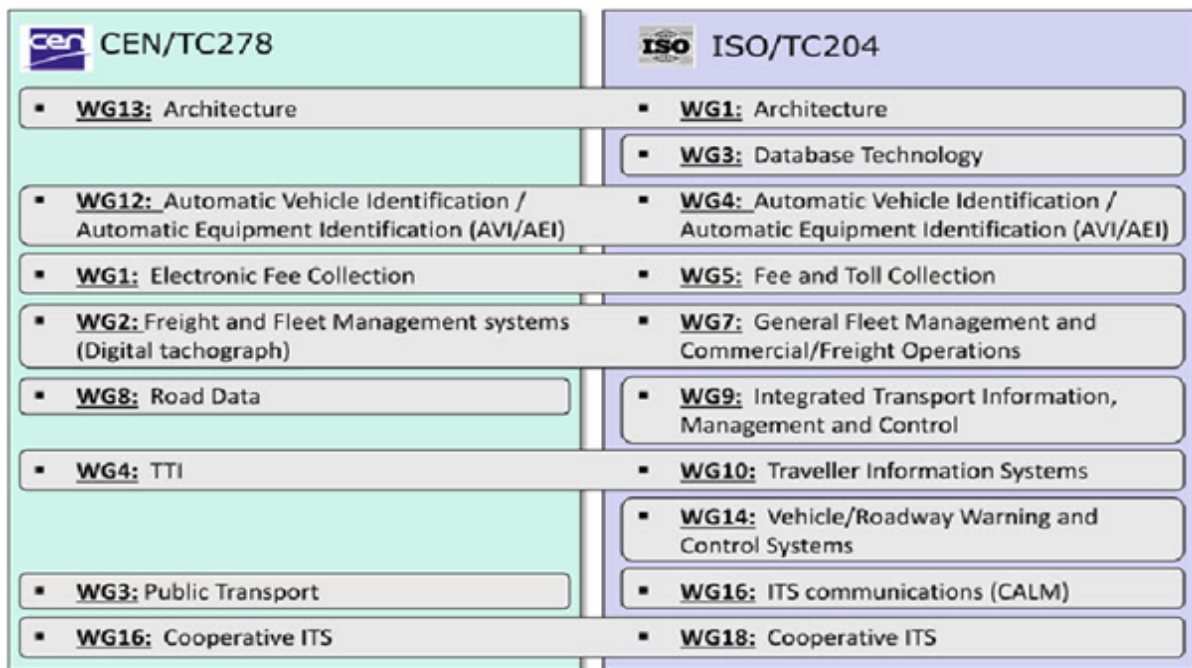


Figure 3.2: Joint development of standards by CEN TC278 and ISO TC204 [2].

3.3 C-ITS system architecture

This section describes the deployment restrictions to build the C-ITS device called the ITS station (ITS-S) in EU or the DSRC Device in the US. C-ITS device is the name of the machine which builds the C-ITS system architecture and implements its applications.

A C-ITS device can be operate while in motion like a vehicle, named as vehicle ITS-S or **On Board Unit (OBU)** and it can be integrated as road side infrastructure known as road side ITS-S or also named as Road Side Unit **RSU**.

Before that an overview of the important standards is given which represent the elementary aspects to build the C-ITS device. They are as follows: the frequency allocation, the communication reference architecture and the message set dictionary.

3.3.1 Frequency allocation

One of the foundations of the Cooperative ITS system architecture (also referred to in the US as DSRC) is the spectrum in which the Vehicle-to-Vehicle (V2V) and Vehicle-to/from-Infrastructure (V2I) communication takes place. In both the US and Europe, authorities have allocated licensed spectrum for this purpose. This section presents a details of these allocations, including frequency ranges,

3.3.1.1 Allocation in the US

The [Federal Communications Commission \(FCC\)](#) is responsible for spectrum regulation in the US [44]. In 1999, the FCC allocated 75 MHz of spectrum in the range 5.850–5.925 GHz commonly called the 5.9 GHz band. The spectrum has seven non-overlapping 10 MHz channels and a 5 MHz unused band dedicated for C-ITS, specifically for the DSRC Service, as shown in Figure 3.3. These 10 MHz channels are numbered from 172 to 184 and also they are able to operate in 20 MHz as well as 175 and 181 each of which overlaps with two 10 MHz channels.

Each one is classified as either [CCH](#) or an [SCH](#), the role of CCH and SCH will be specified in details in the section (section 3.5). The channel 178 is the only CCH and the others six channels are classified as SCHs.

Each channel includes a maximum conducted power in the range of 10–20 dBm to achieve a desired transmission range without causing excess interference at longer distances.

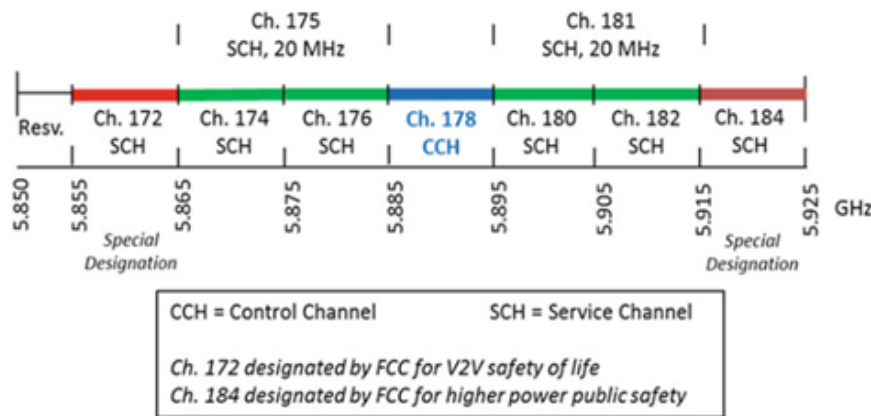


Figure 3.3: Channels allocated in the US by FCC for C-ITS [2].

3.3.1.2 Allocation in the US

The Electronic Communication Committee (ECC) [Electronic Communication Committee \(ECC\)](#) in the EU is responsible for spectrum regulation. In 2008, ECC allocated the European spectrum for ITS communications around the 5GHz band named “ITS-G5” [45]. It has six SCHs and one CCH, as for the FCC spectrum allocation. The Figure 3.4 shows the ECC frequency allocation plan and their different classes, it is divided in to three portions:

- ITS-G5A is a 30 MHz-wide band, in the range 5.875 to 5.905 GHz, contains channels CCH,

SCH1, and SCH2, which are intended to support safety applications;

- ITS-G5B is a 20 MHz includes the frequencies from 5.855 to 5.875 GHz dedicated to non-safety applications contains channels SCH3 and SCH4;
- ITS-G5D is a 20 MHz of spectrum in the range 5.905 5.925 GHz for future ITS extensions.

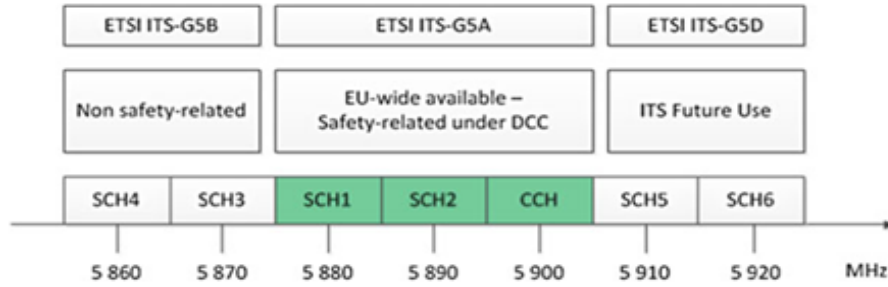


Figure 3.4: ITS carrier frequencies in the EU [2].

As shown in Figure 3.5, each channel in the ITS-G5 band has restrictions in spectral power [46]. Which in turn restrict any Inter Vehicle Communication (IVC) to short range transmissions in order to avoid adjacent channel interferences.

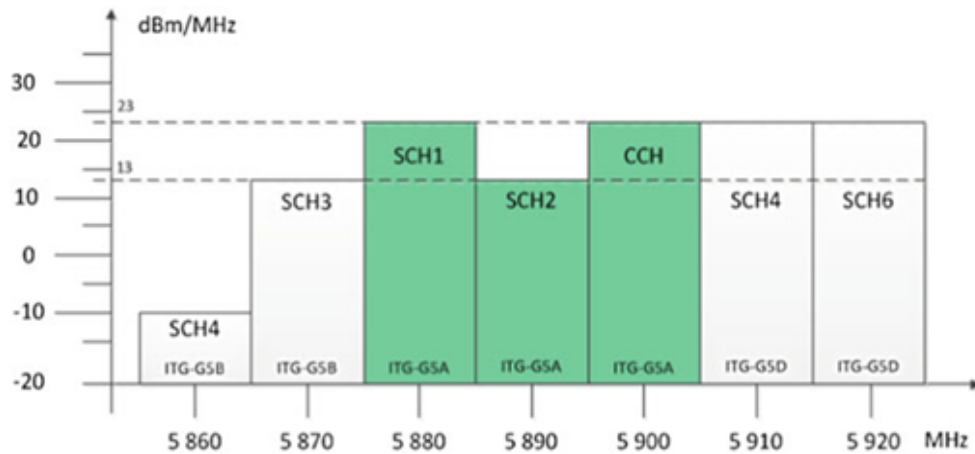


Figure 3.5: Power spectral limits on each ITS channel [3] , adapted from [3].

3.3.2 C-ITS communication reference architecture

3.3.2.1 The WAVE architecture in US

The WAVE approach, depicted in Figure 3.6, is a protocol stack providing a sub-set of the functionality of an ITS device in the USA. It is divided into two parts – safety applications and

non-safety applications and the both parts share the same data link layer and physical layer for transmission. The WAVE protocol stack of safety applications is standardized in IEEE 1609.0 [47]; it describes how the stacks work together. The standards is built on top of IEEE Std 802.11p which Defines the lower layers (PHY and MAC) of the communications stack [48] (see the Section 1.4.1) and it is optimized for fast reliable broadcast of safety messages. The most important parts of the 1609 family of standards are:

IEEE 1609.4 : is a Standard for WAVE - Multi-Channel Operation. It provides enhancements to the IEEE 802.11p Media Access Control (MAC) to support multichannel WAVE operations (Section 3.5.1).

IEEE 1609.3 : is a Standard for WAVE - Networking Services. It defines network and transport layer services, including the **WAVE Short Message Protocol (WSMP)** for efficient single-hop null-networking communications,

IEEE 1609.2 : is a Security Services standard for Applications and Management Messages. It defines secure message formats and processing.

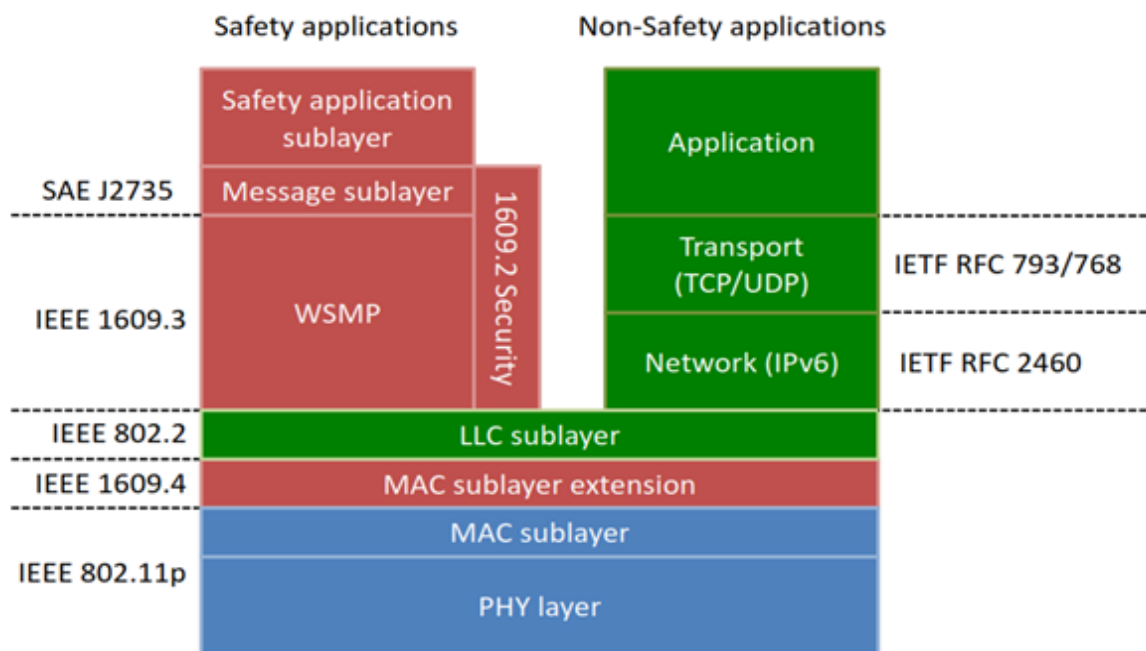


Figure 3.6: The WAVE protocol stack containing both a road traffic safety applications' part as well as a non-safety part [4].

3.3.2.2 The ITS station architecture in EU

The ITS station reference architecture is written by CEN, ETSI, and ISO based on what is already published in ISO 21217 [8] and it is also used in ETSI standard [49]. The system that implements this architecture is denoted as an ITS station (ITS-S), see Section 3.3.4. By using a simplified and extended architecture of the Open Systems Interconnection (OSI) model, the ITS station reference architecture contains the following layers which are interconnected with Service access points (MI, MN, MF, MA, MS, SI, SN, SF, IN, NF and FA) as shown in the figure 3.7:

1. The ITS-S access layer represents the first communication part equivalent to the OSI layers 1 and 2. It contains any type of access technology communications (e.g., infrared, microwave, millimeter wave, IEEE 802.11p, 2G/3G) to provide homogenous connection to the end users and applications,
2. The ITS-S Networking and Transport layer represents the OSI layers 3 and 4. It contains all the types of networking and transport protocol including the Internet Protocol version 6 (IPv6) and CALM Non-IP networking [50] to support some ITS applications [51],
3. The ITS-S Facilities layer represents the OSI layers 4, 5, and 6. It provides a large variety of facilities (e.g., message handling, Local Dynamic Map) supporting various communication protocol stacks according to the needs of C-ITS applications.
4. The ITS-S Management entity and the ITS-S Security entity provide management and security features. The ITS station is defined as a bounded secured managed domain (BSMD) standardized in CEN/ISO 17419 [52], it in order to provide trust to the users.
5. The ITS-S Applications entity is on top of the previous communications layers. One of the most essential characteristic of an ITS station is the abstraction of applications from communications. The ITS-S application protocols [8] are not supposed to know anything about the communication processes of the ITS station unit, but they collaborate with the ITS station management declare their communications requirements as specified in CEN/ISO 17423 [53].

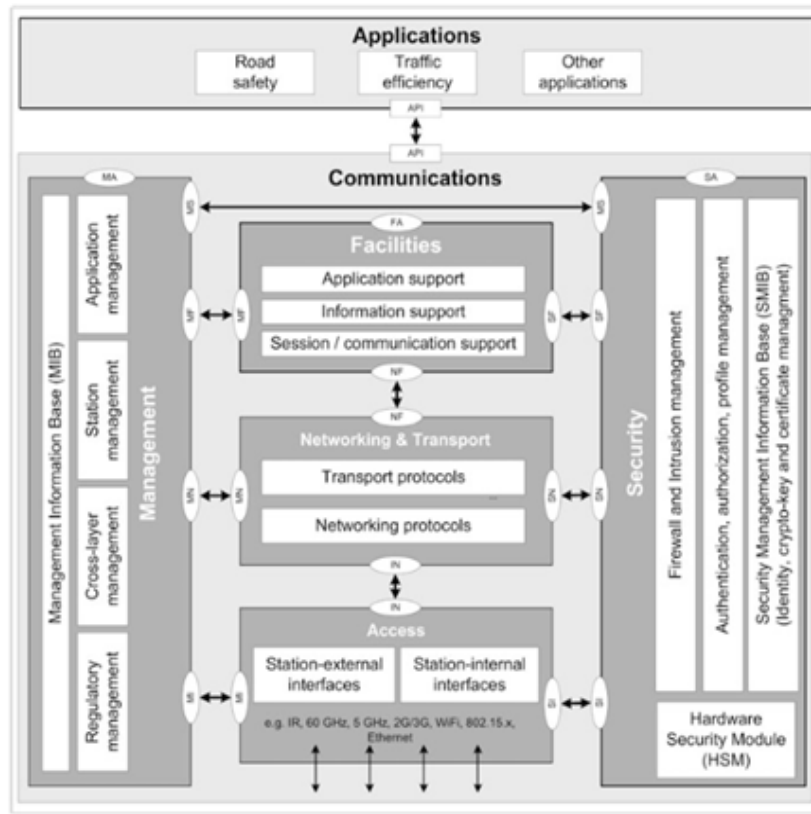


Figure 3.7: ITS station reference architecture [2].

3.3.3 Message sets

3.3.3.1 Overview

This part investigates the core messages sets in EU and North America which are generated by the application or facilities layers entity of the standardized ITS communication reference architecture. The Figure 3.8 shows the set of messages developed in the EU and North America as well as lower layer standards involved in the message dissemination.

Standardization of message format plays an important role to ensure the communication interoperability in the ITS communication system and to support the selected set of applications for deployment. It needs to take into account: application requirements, Message format that defines the syntax and semantics of data being included in a message, Communication capacities in order to avoid useless overload traffic to communication channel And Harmonization of message sets with existing relevant standards in the same region, would facilitate the interoperability between vehicles and road side infrastructures.

The Figure 3.9 presents an overview of V2V and V2I messages sets that are used in ITS

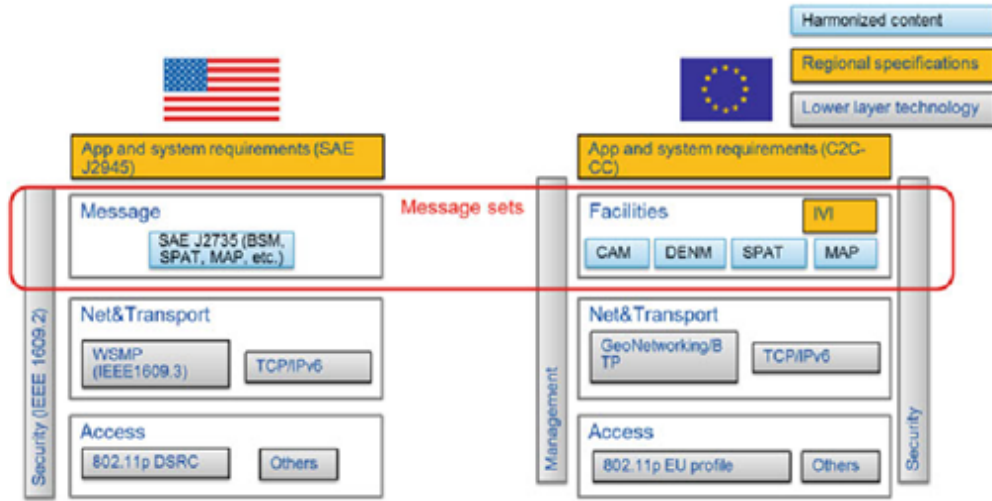


Figure 3.8: Message sets in reference ITS communication architecture [2].

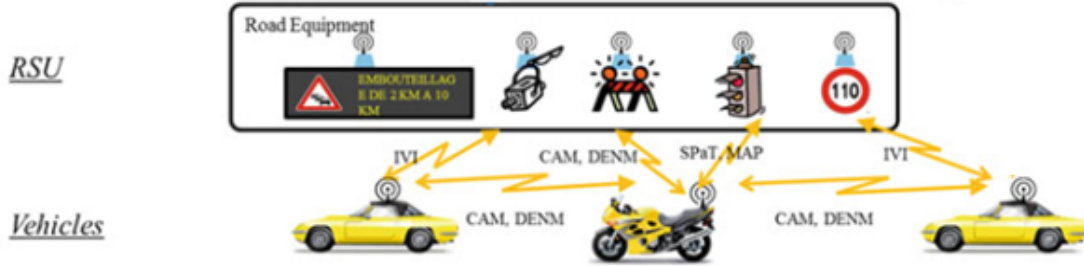


Figure 3.9: High level overview of ITS protocols used in the EU [2].

domain in the EU. In North America, similar architecture may be observed, with corresponding message sets which is standardized by SEA in J2735 [5][9]. The message sets of the figure 3.9 are summarized in more detail as follows:

- Cooperative Awareness Message (**CAM**): It is a hello message (beacon) that is sent periodically from OBU and RSU to announce data about the vehicle itself such as position (latitude, longitude, and elevation), movement, vehicle size, etc. It is for European deployment which is standardized by ETSI TC ITS [54].
- Decentralized Environmental Notification Message (**DENM**) : It is an event driven message sent by OBU and RSU after a detection of emergency situation. It is for European deployment, which is standardized by ETSI TC ITS [55].
- Basic Safety Message (**BSM**): It has the same functions as CAM and DENM dedicated to North American applications. It is for North America deployment, standardized by SEA

TC DSRC [56].

- **Signal Phase and Timing (SPAT)**: It is sent by an RSU working as traffic light to provide phase and timing information. It has been adapted for deployment in North America, EU, and Japan which is standardized by SAE TC DSRC [9].
- **Map Data (MAP)**: It is sent by an RSU to vehicles to provide them road topology information of road segments or intersections. The receiving vehicles map the SPAT data to the intersection topology to match each individual traffic light status data to the corresponding road segment and select the relevant traffic light. It is for North America deployment, standardized by SEA TC DSRC [9].
- **In Vehicle Information (IVI)**: it is sent by RSU to provide road side sign information to vehicles or mobile devices. It is initiated by CEN and standardized by CEN/ISO as world side standard [56] .

The Table 3.1 provides a matching between VANET messages set summarized in this section and the ITS critical safety and road traffic efficiency applications proposed by ETSI TC ITS [9]:

Table 3.1: Matching of ITS applications and VANET messages [2]

Application	CAM	DENM	BSM	SPAT	MAP	IVI
Longitudinal collision risk warning	X	X	X			
Intersection collision risk warning	X	X	X	X	X	X
Traffic light violation warning	X	X	X	X	X	
Lane change warning	X		X			
Cooperative awareness	X		X			
Emergency vehicle approaching	X	X	X			
Slow vehicle approaching	X	X	X			
Emergency electronic brake light	X	X	X			
Stationary vehicle	X	X	X			
Hazardous location		X	X			
Road works warning	X	X				X
Green light optimal speed advisory				X	X	
In-vehicle signage						X
Speed limit information						X

These messages allow transmitting a plenitude of information in the vehicular environment that vehicles will receive from other vehicles as well as fixed road infrastructure to support ITS

application.

3.3.3.2 Beaconing messages in US and EU

Beaconing, or Cooperative Awareness application, is considered as one of the most important application for the day one deployment of VANET system [4]. It periodically transmits a real-time message known as Beacons or heartbeat which contains information of vehicle position, vehicle movement, vehicle basic attributes, and sensor data. Vehicles will be able to create and maintain awareness of each other and to support cooperative performance. The beacon message is standardized in EU as CAM and in US as BSM.

The CAM is generated in the facilities layer without any control of a specific application or use case at the application layer. Its generation is based on vehicle dynamics between 1 to 10 times per second (1-10 Hz) and according to some criteria: the movement over 4 meters, head changing more than 4° and the speed acceleration/deceleration more than 0.5 m/s. The Figure 3.10 shows the CAM packet to be transmitted with the PHY, MAC, LLC, SNAP, BTP and GeoNetworking (GN) headers together which have a fixed size. If the CAM is transmitted with high frequency (HF) when the update rate is 1-10 Hz, the CAM data will be 14 byte and it will be 90 byte if it is transmitted with low frequency (LF) when the update rate is 1-2 Hz. The security will at maximum add 222 bytes [57], thus the resulting packet size will end up around 326 bytes for HF CAM and 402 bytes for LF CAM.

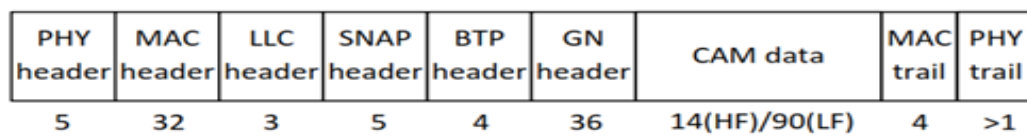


Figure 3.10: Example of a generic CAM packet with the sizes of each field in bytes [57][4].

The BSM is the most central message in the SAE J2735 DSRC message set dictionary [9], which is the basis for a diverse set of safety and efficiency road traffic applications for the WAVE approach. It will be broadcasted with frequency between 1 and 10 Hz depending on driving context and the status of the wireless channel (i.e., Channel busy ratio). The Figure 3.11 shows the packet length for a typical BSM message which will on average be 105 bytes with the fixed packet headers which are PHY, MAC, LLC, SNAP and WSM. The resulting BSM packet length

with the addition of security overhead (222 bytes) will end up around 382 bytes.

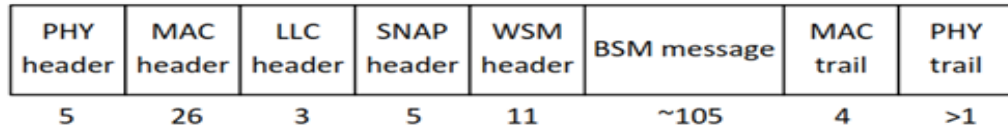


Figure 3.11: Example of a generic BSM packet with the sizes of each field in bytes [4] .

3.3.4 C-ITS device concept

3.3.4.1 DSRC device in US

DSRC device is licensed to operate in 5.9 GHz band and to implement the WAVE communication architecture. Two types of device are defined by the FCC with different status. OBUs are licensed to operate in motion and anywhere vehicles or pedestrians. Whereas, RSUs have to be stationary and they operate in a site or in a region. OBUs may communicate with other OBUs or with RSUs but RSUs are only allotted to communicate with OBUs and not with other RSUs. A new designations to channels 172 and 184 [58] have been updated by the FCC in 2006 at the request of the ITS community. Channel 172 is dedicated exclusively for V2X safety communication where vehicles will exchange BSM, as well as some other messages integrally related to road efficiency e.g., Intersection MAP or SPAT messages. Channel 184 is dedicated specially for longer-distance communications to be used for public safety applications including road intersection collision mitigation. The signal dissemination by emergency vehicles is one key application for Channel 184 where it can send a message to a signal controller without contending with other traffic. So that gives the signal controller sufficient time to react and to clear the intersection. Note that Channels 172 and 184 still being classified as SCHs as the same time as this special new designations.

3.3.4.2 ITS station in EU

ITS station is licensed to operate in ITS-G5 band, based on the ITS-S reference architecture published in ISO 21217 [8] for both static RSUs and mobile OBUs. An ITS-S may contain one or more ITS G5 transceivers which maybe classified into three types depending on their functions: safety-related, traffic efficiency, commercial applications. Each transceiver can operate on single or multiple channels according to the requirements of the ITS applications (operating channels

and channel switching). Obviously, a base channel is assigned for each transceiver configuration corresponds to where it may expect to receive its class of traffic. Each transceiver shall operate in one of the three configuration T1, T2 and T3 as shown in figure 3.12 and as defined in the ETSI specification [59] . The transceiver configurations are presented as follows:

- Configuration T1: It is for a transceiver operating just for safety-related ITS applications and never switch to other channels and must remain to its assigned channel. It is constantly tuned to the CCH to send and receive CAM and DENM when the vehicle is considered in traffic. If other type of safety- related applications are required, such as platooning or highly autonomous driving, at least another T1 transceiver must be available,
- Configuration T2: It is for a transceiver which can operate arbitrary in ITS-G5A or ITS-G5B channels. It may support channel switching mechanisms,
- Configuration T3: The transceiver can be tuned to arbitrary ITS-G5B or ITS-G5C channels. The transceiver of this type can share spectrum with WiFi on the RLAN bands.

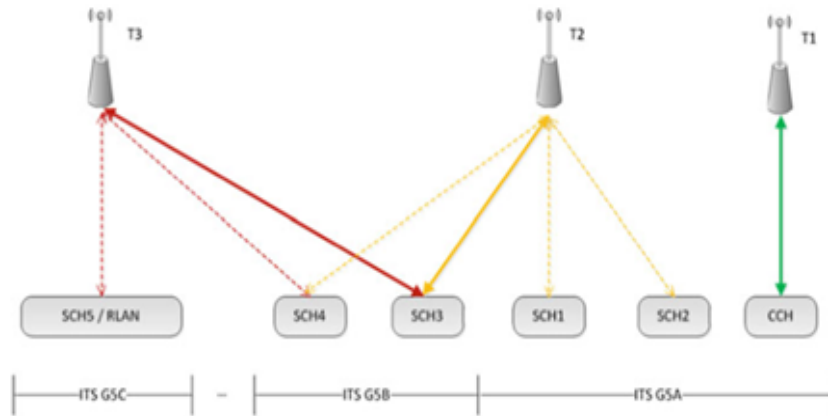


Figure 3.12: ITS-S types and restrictions as defined at ETSI [2] .

3.4 Standardized channel Access Mechanisms

Channel access protocols for C-ITS have the most import part in ITS device architecture. It has the responsibility to ensure an efficient sharing of the radio channel resources between competitors. In the context of C-ITS, the channel access protocols have to be distributed contrary to centralized approaches like WLAN and cellular network.

Distributed channel access mechanisms (DCAM) for C-ITS have three operations, which are: the Multiple Access Control (MAC), the Distributed Congestion Control (DCC) and Multi Channel Access (MCA). The MAC has a direct impact on the performance of C-ITS applications while DCC and MCA mechanisms provide additional improvements of the MAC efficiency which are adopted in the standardization process.

3.4.1 Multiple Access Control

The MAC layer plays a crucial role in regulating the access to the common wireless medium, it detects the state of the channel busy or idle, and properly reacts when a transmission has failed. It provides fair access to the vehicular channel, so that multiple vehicles share its efficiently. In a vehicular environment, the most important requirement for a MAC is to ensure a decentralized operation, without central node in charge or a coordinator to manage the channel access or the resource assignment. In this case, vehicular nodes are able to communicate without waiting for the association with the node playing the coordinator role. Among existing radio technologies, the simple well-known IEEE 802.11 [60] technology was considered as the best candidate to support V2X wireless communications. Its amendment IEEE 802.11p is now represents the de facto solution for C-ITS communications. It is one of the few shared between the WAVE architecture in US and ITS station architecture in EU.

This section gives an overview of the IEEE 802.11p standard as well as the challenges imposed by the constraints and peculiarities of VANETs and also the methods to evaluate the MAC performance.

3.4.1.1 IEEE 802.11p MAC foundations

Network establishment (Topology) IEEE 802.11p [23] inherits the main rules of the baseline 802.11 MAC standard which is build upon the concept of Basic Service Set (BSS) Basic Service Set (BSS) as a set of stations exchanging data. The standard has specified two types of BSS which are: infrastructure and independent BSSs (Figure 3.13). In an infrastructure architecture the BSS is established and announces by an Access Point (AP) which send periodically beacon messages. When a station listens to the beacon, it can join the BSS through three steps: synchronization, authentication, and association. On the other hand, in an Independent BSS (IBSS) (also called an Adhoc Network), the communication directly happened between stations

without AP. Every station announce the existence of the IBSS by transmitting beacon messages to allow synchronization of stations. Both infrastructure and independent BSSs can be supported by IEEE 802.11p, where their operations for authentication and association are considered too time-consuming in high mobile environment such vehicle networks. For that a new operational mode has been introduced in 802.11p referred to as **Outside the Context of the BSS (OCB)** that avoids the latency related with establishing a BSS. In OCB mode, vehicles which are not member of a BSS are allowed to send data without association signaling and any required authentication service would be provided by the upper layers for security purposes.

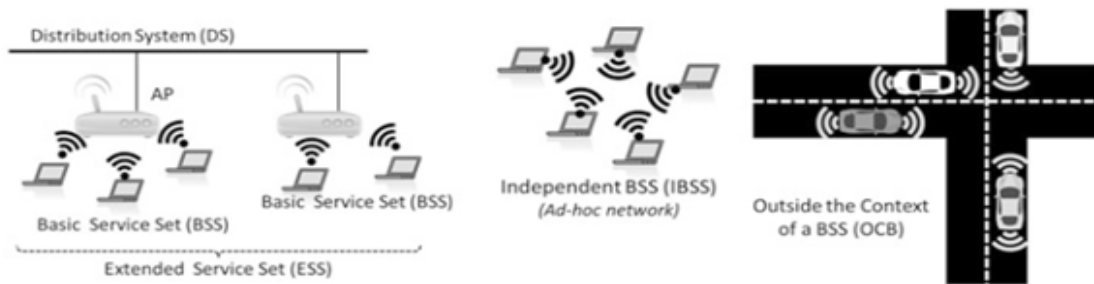


Figure 3.13: IEEE 802.11 modes: infrastructure mode (BSS), ad-hoc mode (IBSS), and the new OCB. Nodes in a VANET are free to use any of them (BSS, IBSS, OCB); but, OCB is specifically for medium access with rapidly moving node [2].

The channel access method

The IEEE 802.11p MAC layer manages three types of messages: Data, Management and Control messages. Data messages contain user data received from application layer. Management messages (e.g., beacon) enable vehicles to award about their environment received from upper layers. Control messages, e.g., Request-to-Send (RTS), Clear-to-Send (CTS) and acknowledgement (ACK), assist in the exchange of data and management messages between vehicles. The IEEE 802.11p uses the QoS amendment of the MAC layer of IEEE 802.11e together with the PHY layer of IEEE 802.11a [61] which has been changed to fit the high-speed vehicular environment. The transfer rate is halved in 802.11p as compared to the original 802.11a, because it is designed for 10 MHz wide channel instead of 20 MHz, so that the transfer rate will take following values: 3, 4.5, 6, 9, 12, 18, 24, and 27Mbps.

A distributed channel access scheme is the best candidate for ad hoc communications in IEEE 802.11p. Its MAC method is called **Enhanced Distributed Channel Access (EDCA)**, which is the improved version of the Distributed Coordination Function (DCF) **Distributed Coordination**

Function (DCF) mechanism used in 802.11. EDCA relies on the CSMA/CA technique to reduce the probability of collision between multiple vehicles accessing the medium.

Its mechanism is categorized as contention-based approaches based on carrier sensing (CS), back-offs, and retransmission schemes:

- Carrier sensing: The basic idea of CSMA/CA is “to listen before talk”, meaning that the station starts by assessing the channel before transmission to determine whether it is busy or not. Clear Channel Assessment (CCA) is the name for the channel monitoring and it can be performed both through physical and virtual mechanisms. Physical carrier sensing consist of listening to the channel and if it is free for a certain period of time, called an Arbitration Interframe Space (AIFS), the sender can transmit directly so that the direct collisions can be avoided. Physical carrier sensing is ensured by controlling any channel activity done by other vehicles, by measuring the energy in the surrounding (Energy Detection) and recognizing the message preamble. The hidden terminal problem represents a big challenge for the Ad hoc network, the hidden terminal is a vehicle which is located out of the range of the sender and at the same time close enough to the receiver so that it disturbs the ongoing transmission so that a hidden collision will be happened. Physical Channel sensing is not sufficient to avoid the hidden collision in 802.11-based networks. Therefore, the Virtual sensing is, instead, introduced by adding a preliminary RTS/CTS control messages for handshaking between the sender and the receiver to reserve the medium before the actual data exchange. During the transmission, the other vehicles set a counter called NAV to defer their transmission until the channel becomes idle. The NAV is decremented by slot-by-slot to keep track of the channel status and once the NAV reach zero the transmission take back.
- Back-off: If the channel is busy during the AIFS, the vehicle wait for the channel to be free again and perform a backoff to defer its access which is a randomized period of time generated from a CW. The QoS in EDCA uses four different priority queues or Access Categories (ACs) , namely voice, video, best effort, and background where the data messages are placed. Each ACs has specific AIFS and backoff parameters, i.e. the higher priority, the shorter AIFS and smaller CW, as shown in Table 3.2. Its procedure works as follows: (1) draw an integer number from the interval $[0, CW]$ with uniform distribution

(2) the backoff value is computed by multiplying this integer number with the slot time of the used PHY layer , (3) when the channel is sensed free decrease the backoff by one slot, (4) once the backoff reach the value of 0, send immediately.

- **Retransmission:** The MAC protocol of 802.11 is a stop-and-wait protocol and after sending a message, the sender will wait for an ACK. If it does not be received for some reason, the retransmission of the message will be launched to give an other chance for those how want to send over a longer time period. Before every retransmission attempt, the size of CW will be doubled from its previous value and a backoff procedure must be invoked. After a successful transmission or when the message had to be thrown away because of reaching the maximum value (CW_{max}), the CW will be set to its initial value again (CW_{min}).

Table 3.2: Default value of the CW_{min}, CW_{max} and T_{AIFS} for the different ACs in 802.11p

AC	CW _{min}	CW _{max}	T _{AIFS} [μ s]
AC_BK	15	1023	149
AC_BE	15	1023	110
AC_VI	7	15	71
AC_VO	3	7	58

With the broadcast scenario, the message is sent to every vehicle inside the transmission range, not to a specific receiver and if the receivers return their ACKs, a multiple collision will be happened. Thus, this kind of communication does not use most of the CSMA/CA mechanisms that rely on the receiver's feedback. Therefore, no ACK will be sent by the receiver and the sender will never know if the surrounding vehicles have received the transmission message correctly or not. Moreover, the broadcast messages will never experience multiple retransmissions and backoffs, the contention window will always be in its initial value (CW_{min}) and the sender will perform just one backoff when it senses a busy channel. As a result, the prevention of hidden collisions is not as effective as in the unicast transmission, as shown in Figure 3.14.

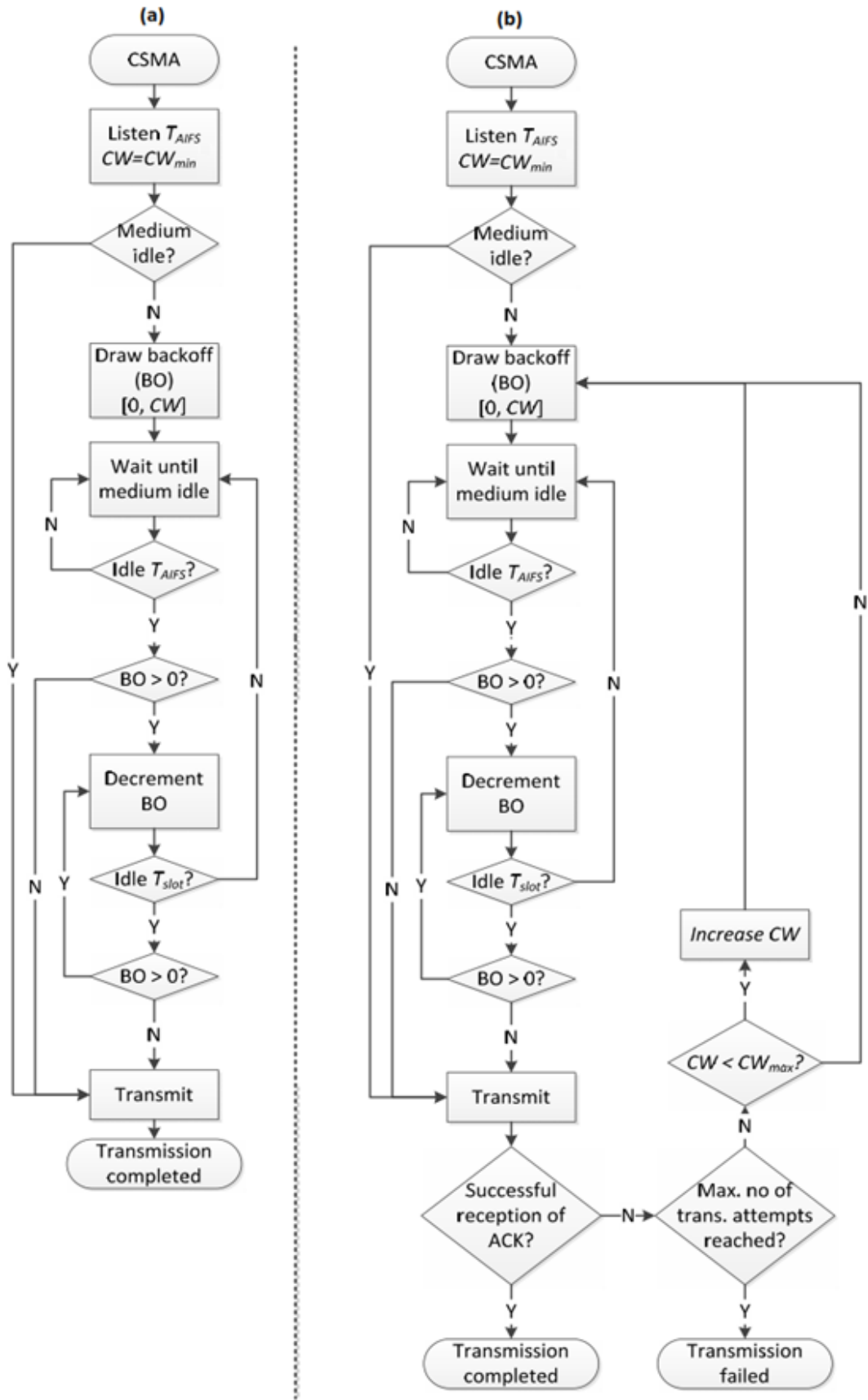


Figure 3.14: CSMA channel access procedure; (a) broadcast mode, and (b) unicast mode [4] .

3.4.2 Decentralized Congestion Control

The challenges imposed by VANET specification make the adaptation of IEEE 802.11p to vehicular environment a hard task, especially with safety communications requirements which are based on broadcast communication. This kind of communication kills the feedback mechanism used by the MAC layer of IEEE 802.11p and causes a high congestion on the channel. Therefore, the problem of collisions in VANETs is increased and channel access delay becomes unpredictable and both reliability [62] and fairness [63] are affected. A DCC is proposed in order to avoid the MAC limitations and challenges. This section, presents the principle of DCC and its cross layer aspects.

3.4.2.1 Challenges and VANET requirements

The MAC protocol for VANETs is exposed to some serious challenged imposed by the vehicular environment and by the nature of communication which are shortly resumed as follows:

- **Communication requirement:** The MAC operation should meet the road safety application requirements which are differ from the other applications in that (1) Reliability, (2) Delay and (3) Fairness. Safety applications require a High reliability which means messages must be received correctly and Predictable delay which means that a message needs to be delivered to the receiver before a predefined deadline [62]. This predictability is sometimes termed real-time, either it is critical before a traffic accident as with DENMs or before an expiration time where a newer version is available as with CAMs. Fairness is to give all vehicles at least one opportunity to access the channel within each period of time [63] .
- **Mobility:** The high mobility of vehicles and the rapid changing network topology causes a short connection lifetime between vehicles. Therefore, CSMA/CA protocols should support this feature by being decentralized and connectionless.
- **Hidden terminal problem:** It is known that hidden terminal occurs when at least three vehicles, let us say A, B, and C, are positioned in such a way that B can hear both A and C, but these two cannot hear each other. For this reason. In the other hand, Broadcast protocol is the base of the most vehicle traffic, especially safety communications. Its principle is to send packets to all vehicles in a specific range which makes the feedback an

expensive and difficult task under Broadcast communication. Therefore, no prevention of hidden terminal by the CSMA/CA mechanism that relies on the receiver's feedback and the collision avoidance is not so effective as one could expect.

- **Scalability and Congestion Problem:** In VANET, the number of vehicle cannot be known and predictable and impossible to be restricted. The only known information is that sparse traffic conditions are common in off-peak hours and high traffic conditions with several cars concentrated in a small area characterize instead urban crossroads in peak hours. In the latter case, the data traffic load is considerably heavy, especially with safety data, such as Cooperative Awareness Messages (CAMs) which is transmitted by vehicles frequently.

This situation causes a high congestion on the channel and increases the problem of collisions in VANETs: this threat led to the use of DCC mechanisms.

3.4.2.2 Congestion Control principal

DCC mechanisms have been proposed to overcome the CSMA/CA poor performance in VANETs and to give the upper layers (the application or Facility Layer) the possibility to enhance the MAC inefficiencies. The goal is to minimize packet collisions and ensure fairness channel access to all the stations under a high channel load and a fast network topology changes.

Since communication channel access in 802.11-based wireless ad hoc networks is performed locally without the coordination of a central scheduler, the DCC mechanisms is used to have a global view of channel load [64]. The principle is that every node uses the global channel load as input to control and limit the individual channel utilization as an output result (e.g., transmit rate, output power...), in order to avoid an overall channel congestion. The channel utilization of all nodes gives in turn the new global channel load. This is called the DCC control loop as shown in Figure 3.15 [2].

The most important inputs to DCC which measures the channel load are the number of neighbors and **Channel Busy Ratio (CBR)**. The former is can be made available via the neighbor table associated with the networking layer (see Figure 3.17) The latter CBR is the ratio of the time the channel is perceived as busy and the overall observation time. A high number of neighbors station within a communication range and a high transmission rate (the generated packet rate), one of them or both, can cause a high channel load.

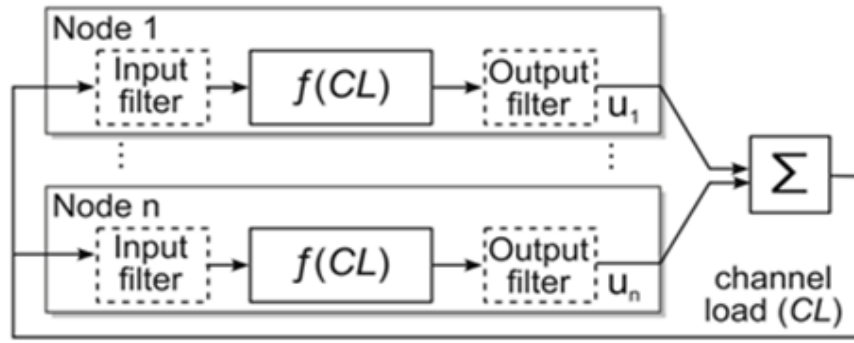


Figure 3.15: DCC control loop model [2].

The outputs of DCC are the factors which affect the transmission behavior. There are mainly three factors available for DCC which are standardized under the TS 102 687 [65] by ETSI TC ITS in July 2011:

- **Transmit Rate Control (TRC)** : It consists of adapting the number of generated packets (safety beaconing with CAM/BSM) according to the channel load. In a congested environment the frequency of the safety beaconing has to be reduced, but such an adaptation has to perform carefully because sending less than a certain threshold may damage the performance of the application instead of improving it.
- **Transmit Power Control (TPC)** : The goal to increase spatial frequency reuse. It is about controlling the transmit power level or output power level per packet by adapting (reducing or increasing) the output power depending on channel activity. The transmitting power level determines the spatial utilization of the channel. So it affects the number of vehicles will receive the packet. With low transmission power, only the closest neighbour may receive the packet. With high transmission power, a significant number of vehicles might receive the packet, but the collision probability increase too, so that it has to be used carefully. Moreover, if the contending vehicles use a different transmits power level, the channel cannot be shared fairly and several hidden collisions can happened.
- **Transmit Data Rate Control (TDC)** : It influences the transmit durations of transmitted packets. Since 802.11p offers several transfer rates, where 3 Mbps is the lowest, Stations can use high transfer rates to decrease the channel transmission duration, and as result the channel occupancy can be decreased. Note that, the lowest transfer rate has the most

robust modulation and coding scheme and this choice is made for the safety application when the high reliability is required rather than high throughput. This output parameter is not further used in DCC standardization.

3.4.2.3 Cross layer aspects

The DCC mechanism should not only be focused on the MAC layer, it has been divided between the management plane, MAC layer, network/transport layer, and application/facilities layer, connected in an cross-layer issue as shown in Figure 3.16. The DCC components are spread throughout the C-ITS protocol stack.

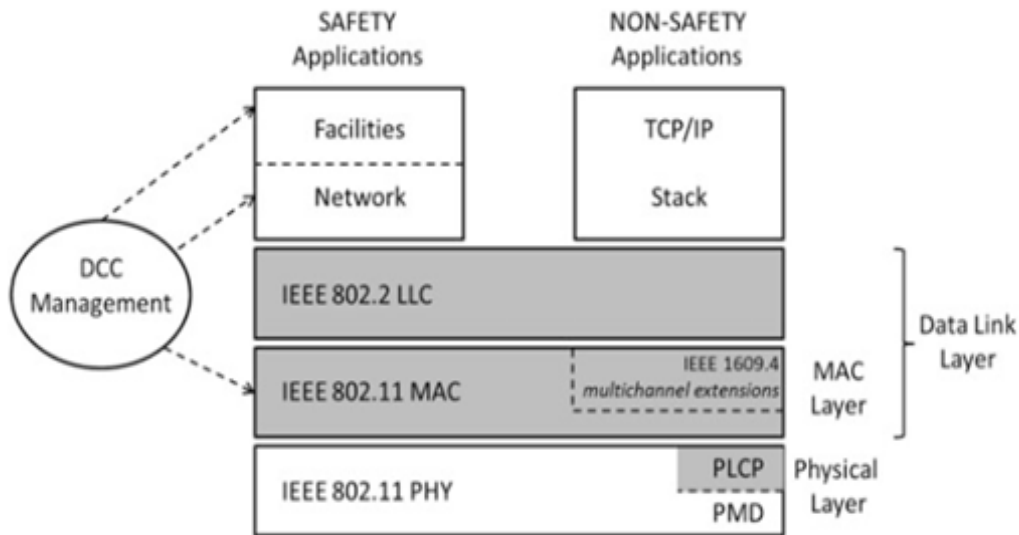


Figure 3.16: Cross-layer DCC by ETSI and IEEE [2].

The MAC layer will provide the channel activities (CBR estimation) as mentioned in the standard ETSI EN 102 687 [43]. The network/transport layer will provide the neighbor table containing the information about the stations which contribute in the channel load as standardized in ETSI EN 102 636-4-2 [66]. Since the facilities/application layers generate the packets to be transmitted, using information about the channel load by these layers can reduce the congestion on the MAC layer, as standardized in ETSI EN 103 141 [67]. These interactions between the layers are shown in details in Figure 3.17. The DCC algorithm will then limits one of its factors which the packet generation rate and control the input packets into the MAC layer queues. The objective is to adapt it to the safety needs and distribute the channel resources

equally between all contending stations. As an example the frequency of CAM is standardized in ETSI EN 302 637-2 [68] to be generated according on the vehicle speed.

In Europe, it has been a consensus view at the end of 2015 on DCC for the C-ITS protocol stack. On the other hand, DCC for DSRC has been an active research field in the USA for several years, both in the academic and industrial communities.

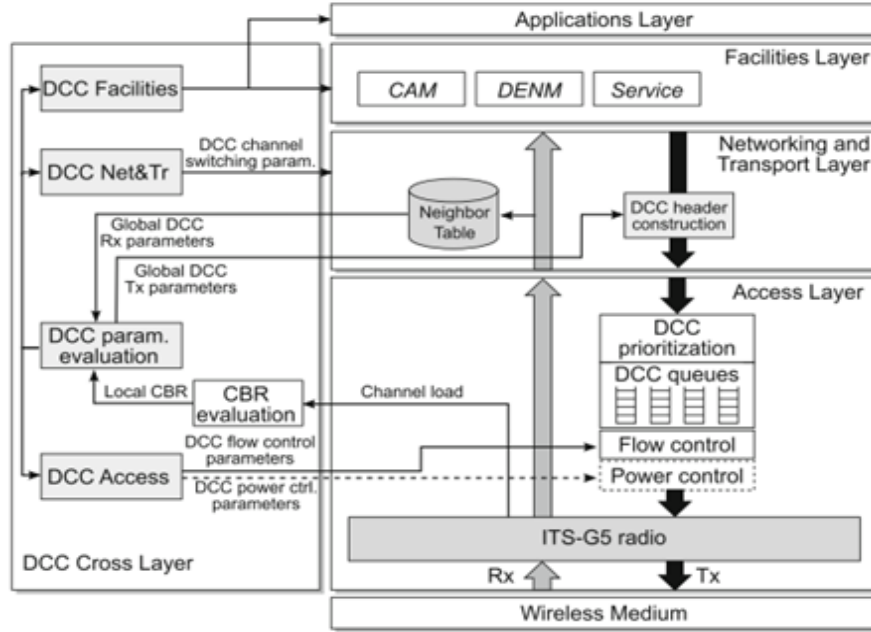


Figure 3.17: DCC in the ETSI ITS station architecture [2].

3.4.3 Multi-Channel Control

The day One deployments of C-ITS consider the road safety applications and involve, exclusively, the transmission of safety-related messages CAMs/ BSMs and DENMs on single common channel called control channel, CCH in the EU, and Channel 172 in the US. The Day two deployment of C-ITS integrates a new safety application such as autonomous driving or platooning and consider the other types of applications (road-efficiency and Value add-service) and the co-existence of DSRC with non-ITS technologies like 5G and WIFI-Giga. Considering the limited capacity of the control channel, the need of smart and dynamic multi-channel mechanisms becomes critical.

3.4.3.1 Multi-channel operations and applications

The idea of Multi-channel operation is to set a given transceiver to several wireless channels at different times. This operation is called channel switching. Since the C-ITS communications have a large number of available channels, the Multi-channel operation is the best solution rather than statically assigning one transceiver to each channel. Multi-channel operations have three applications:

- **The multi-channel congestion control** : which aim at mitigating the communication load on the control channel by sending some type of traffic to the adjacent channels. So, they allow using the capacities of all available channels efficiently and give the opportunity for different technologies to coexist in the same spectrum bands by moving between the channels [42] .
- **The multi-channel service management** : which specify mechanism for Service Providers (SPs) to offer services to Service Consumers (SCs) on different channels. Therefore, they must rendezvous for service announcements in the control channel, and they dynamically switch to the corresponding channel where the service is actually being offered [69] .

3.4.3.2 Channel switching in US

The transmission of the safety traffic (BSM) is known to be transmitted in the channel 172. But for the non-safety application, the traffic could be sent in any of the other channels. On top to the MAC layer, the IEEE 1609.4 [5] standard supports the channel switching mechanism as an option. The C-ITS device might have one or multiple radio with the possibility to switch, or not, to different channels. The common configuration expected to be used for OBUs is to have two radios, one is permanently tuned to channel 172 dedicated exclusively for safety communication, and the other one is used for the switching mechanism to access services.

According to the IEEE 1609.4 standard, the switching mechanism executes the following paradigm. All participating C-ITS devices are synchronized with the GPS second boundary as a common clock. The time is sliced into a periods of 100 msec called Sync Interval which is divided also into two alternating intervals 50 msec each. The first is the Control Channel Interval (CCH Interval), while the latter is the Service Channel Interval (SCH Interval). Each

of these intervals begins with a short Guard Interval. Therefore, the C-ITS devices can know the active interval at any time, as shown in Figure 3.18.

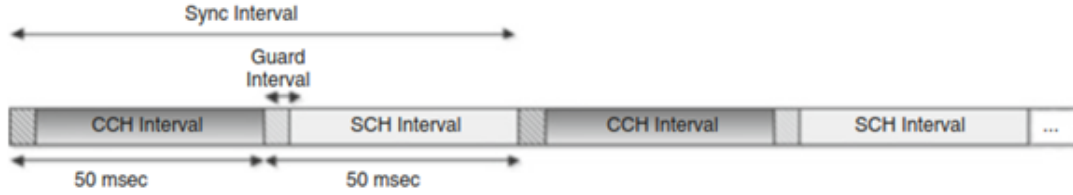


Figure 3.18: Channel switching as defined in IEEE 1609.4 [5] .

3.4.3.3 Channel switching in EU

According to the ETSI specification [33] , has a big similarities with IEEE 1609.4. Only safety-related traffic are sent on ITS-G5A channels (CCH, SCH1 and SCH2) where CCH as primary channel. However, when the channel load reaches the maximum limit or if other type of safety-related applications is required, such as platooning or highly autonomous driving. Therefore, these packets will be transmitted on the alternate channels where SCH1 as secondary channel. On the other hand, The ITS-G5B channels (SCH3 and SCH4) are dedicated to transmit the non-safety-related traffic (services traffic).

For that, two configurations are proposed according to ETSI specification. Configuration T1 is for a transceiver operating just for safety-related ITS applications where the traffic is sent on ITS-G5A channels. Configuration T2 is for a transceiver which can support channel switching mechanisms between ITS-G5A (SCH1 as primary channel) and ITS-G5B to transmit safety and services traffic.

The synchronous channel switching mechanism is very similar to IEEE 1609.4, but restricted on SCHs channels. The ITS-G5 T2 transceiver has two switching phases [70] , as presented on Figure:

- Safety: tuned to the SCH1 during a period of time at least 100 msec where service providers and service consumers must first rendezvous for service announcement.
- Service: tuned to the ITS-G5B channels (SCH3 and SCH4) during a period of time at least 100 msec where they rendezvous again to offer the service announced before.

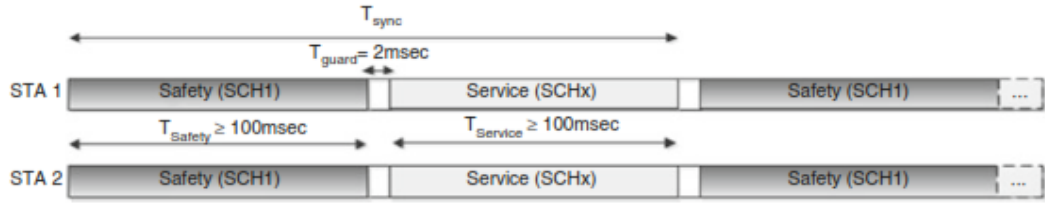


Figure 3.19: Channel switching as defined in IEEE 1609.4 [5] .

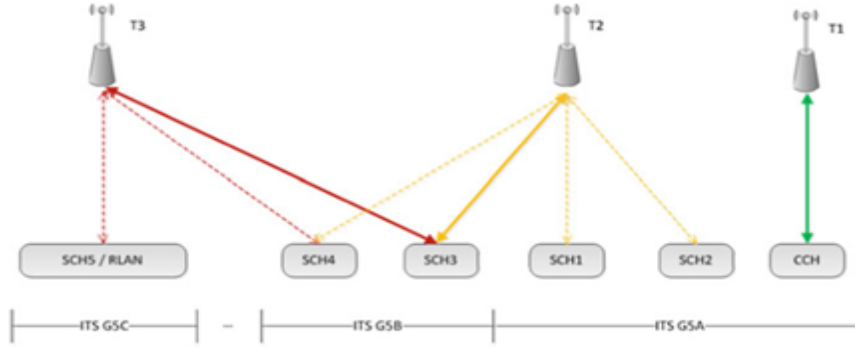


Figure 3.20: ITS-S types and restrictions as defined at ETSI [2].

3.4.4 Performance Evaluation

Since the performance of VANETs applications is affected directly by the MAC phenomena, the evaluation of MAC behavior become an important need. Therefore, the tools used for MAC's behavior evaluation can range from the most practical to the most theoretical. They include (1) Simulations, (2) Analytical models and (3) testbed or real measurements. Each method has its own benefits, limitations and metrics? This section gives an overview of each on these tools.

3.4.4.1 Simulation

Simulation is considered as the most used approach for VANETs studies and the reason of this success is that the simulation tools have a remarkable benefits. A lot of simulation platforms are cheap and open source and easy to use, even beginners can run simulation with modest effort, and they are more and more accurate. Moreover, simulations can test heterogeneous scenarios, involving a large number of nodes, with different settings just by changing the script and in repeated way which is an issue in field tests. Additionally, the growing computational capacity and the cloud computing technology give the possibility to simulations to be launched simultaneously from several places [71] . But, the two major conceptual benefits of simulator

are: the (1) heterogeneous modularity and (2) flexible metrics definition [2].

The modularity which is referred to, consider that each part of simulation relies on its specific simulator, for example application, mobility and communication, ect, as shown in Figure 3.21.

They can be classified as follows:

- Application simulator: It implements the basic set of application defined by ETSI TC ITS [72] , which are classified into three groups: safety, traffic efficiency and value-add service application. Generally this part of simulation is integrated into the network simulator.
- Network simulator: It focuses its simulation on the protocol functioning for information dissemination schemes, starting from MAC layer to the upper layers, unicasting or geo-casting protocols [73] and broadcasting or beaconing [74] protocols such as BSM and CAM might be required for C-ITS applications. Typically it adopts simplified physical signal propagation and reception models. The most popular and frequently used tools for network simulation are: NS-2 and its successor NS-3 [75] , OMNeT++ [76] and JiST/SWANS [77] , they are Open Source and distributed free for non-commercial.
- PHY simulator: It is integrated with the network simulators as a separated module of the physical layer simulation. It is a refined model for signal receiving and propagation which leads to very precise simulation results [78] .
- Mobility simulator: It provides the mobility file which contains the time-dependent position of each vehicle. There are two approaches of extracting it, according to the vehicular application studied which defines the type of interaction between mobility and communication. With the value-add application, mobility of vehicles does not need to be influenced by vehicular communication. So the common approach for this kind of applications is to generate the mobility file apriori and may later be integrated into the network simulated, as shown in Figure 3.22.a. The popular mobility generator tools for this kind of application are as follows: IMPORTANT [79] , GrooveNet [80] , MoVes [80] , and the City Model [81] , VanetMobiSim [82] , SUMO [83] and The commercial simulation software VISSIM [84] . Considering safety and road efficiency application where mobility and communications shall influence each other, a bi-directional interaction has to be created between the two simulators with a complete mutual feedback. So that, depending on the mobility patterns

the vehicular applications will be triggered for example the safety critical message will be sent as a reaction to notified traffic accidents and road congestion events, and depending on the messages received the mobility pattern will change, as shown in Figure 3.22.b. The simulation tools of this category have to integrate both mobility and network simulation with real time interacting. The most promising candidate tools are: Veins [85] , iTETRIS [86] , and VSimRTI [9] .

- Visualization tools: At the end of the simulation, very complex results are generated and here comes the need of correctly interpreting these results. Using visual tools which support data analytics by animating the movement of vehicles and showing how the metrics may evolve by displaying them as colormaps and labels. Visualization can facilitate the interpretation of results.

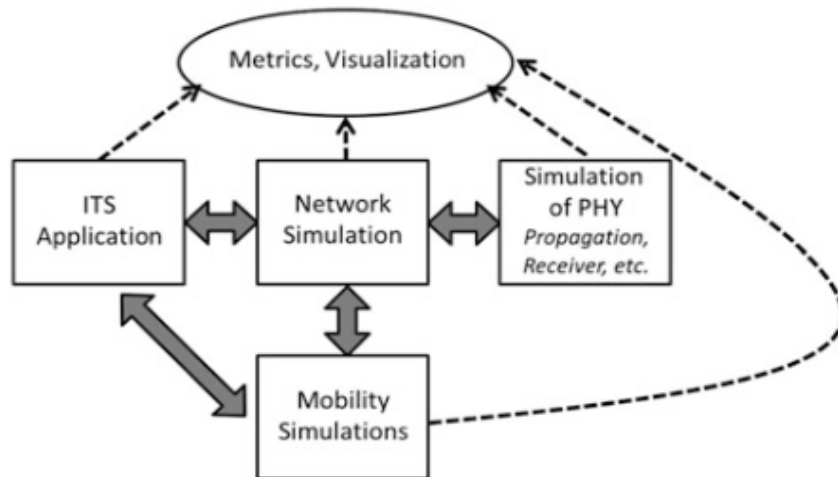


Figure 3.21: Channel switching as defined in IEEE 1609.4 [5] .

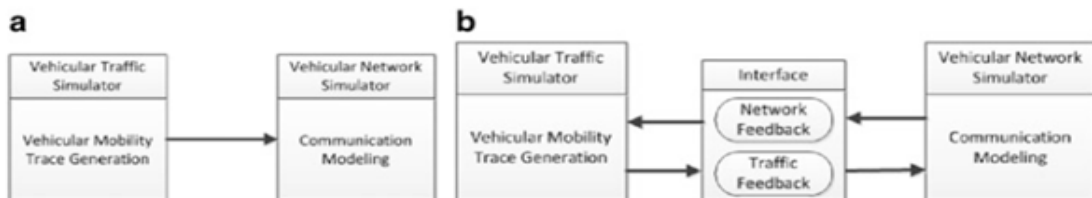


Figure 3.22: Interactions between mobility and network simulators. (a) Isolated case. (b) interactive case [2].

The flexibility of the evaluation metrics is the second benefit of simulation. It gives the

possibility to manipulate the outcomes of simulation the events occurred by the vehicles and their internal states (like position and time) with several ways. Therefore, it allows to make a good study and evaluation of the protocol performance. For example, it is possible to split the events into category (transmission collisions) or into their causes (simultaneous transmission, hidden terminals), and to study the distribution of internal states like the channel load and to perform the correlation between multiple events. The metrics can be interpreted according to several parameters, such as the distance between the transmitter and the receiver, the number of vehicles or their local density, the transmission parameters (power, rate), topology, etc.

At the beginning of the study, it is preferable to start with simulation which can help in the reasoning of the real facts, however, it shouldn't be considered as a goal but as a temporary tool.

3.4.4.2 Mathematical studies and Modeling

Mathematical studies and modeling is a very useful means to evaluate the performance of protocols including the MAC protocols behavior. Their advantage is they do not consume time and resources than simulation. They permit the understanding of the interactions between the protocol's processes and model their behavior. Moreover, the performance of the protocol can be predicted depending to different situations, so to have suitable decisions about the parameters setting and enhance the protocol functionality. However, mathematical models need a typical simplification and sometimes unreal suppositions to make the problem mathematically modeled. This is totally true especially in a complex environment like VANET where there are variable density, mobility and signal propagation conditions which decrease the possibility of accurate modeling. The results of a mathematical model have to be validated by simulation or real experimentations to see how far the predictions are from the real world. As an example of MAC context, the standard 802.11 has been modeled by several mathematical approaches to study its dynamics. For example back-off procedure is modeled by the probability equations like geometry distribution [87] (p-persistent) and Bernoulli [88], the broadcast protocol is modeled by Markov chains [89] (Bianchi's model) and the packet generation and reception rate is modeled according to Poisson process [90], [91].

3.4.4.3 Practical experiment

Measurements in the real world still a necessary step in order to validate the efficiency of the proposed protocol, whatever are the algorithm implemented in simulation and the model used in mathematical study. In general, simulation and mathematical modeling suppose simplified hypotheses whose correctness may hold only under some conditions, as an example in modeling a specific propagation model is used where is the lack of interference and several phenomena occurring in the physical layer are neglected or modeled in a simplified way like attenuation and fading. Furthermore, they do not allow discovering physical phenomena which have not been modeled because they just happen in reality, for example, hidden terminals had been neglected in simulation, not intentionally, until discovered in real tests. Consequently, results will be depending on the initial suppositions. To be fair, practical experiments gives the ground-truth of a solution. However, they have some limitations which are needed to be improved. In that, some results are often difficult to be explained and the reason of the phenomena is not known. For example, let the percentage of a received packet at a given distance be 70 %, it is hard to know if it is due to collisions, interference or the attenuation and fading. Real tests are time consuming and require a special setup; additionally, it is difficult to involve a considered number of nodes in the field. Altogether, it is better to make practical experiments to understand simple phenomena like receiving characterization, attenuation/fading, antenna effect, background noise or to identify novel phenomena to be modeled. The generated realistic data is used then to feed simulation tools, so to study complex cases depending on realistic starting point. For example, the use of a new propagation model based on real measurements to study the hidden terminal in the center of the crossroad [92] .

3.4.5 Evaluation metrics

The MAC metrics which have been frequently used in the scientific literature, are presented in the table x. However, they allow also to evaluate the efficiency of DCC algorithm. The MAC metrics are grouped in three categories:

- **Legacy metrics** which are used to evaluate all VANETs applications,
- **VANET metrics** where the metrics defined in this area refers to a scenario of periodic traffic (CAMs) rather than event-triggered Messages (DENMs).

- **Channel metrics** which measure how the channel reacts to a given protocol,

At the beginning of the study, it is preferable to start with simulation which can help in the reasoning of the real facts, however, it shouldn't be considered as a goal but as a temporary tool.

Table 3.3: ITS applications requirements

Legacy metrics	MAC layer delay	Duration between sending a message down to the MAC layer until receiving it at the MAC layer of the receiver including the access time (backoff count down and freezing), queuing delays and the sending of packet. Can be given for any pair of sender and receiver.
	Transmit rate	Number of transmit opportunities during a given period of time of a given station.
	Packet collision rate	Rate of average transmission collisions due to synchronous and hidden terminal transmissions. Can be given for a single receiver.
	Average Beacon Collisions Probability	The total number of collisions detected by the receiving antenna, divided by the total number of messages sent within the communications range (the same collision, when detected by several vehicles, is considered as a single collision).
	Protocol Overhead	This metric is related to the additional information, called control information, which is sent with the relevant information to enhance the ideal reception by ensuring a smart spatial multiplexing of simultaneous transmission. A protocol may use important overheads but lead to an ideal reception. Therefore, reducing the overhead should not be a goal, but just can be a sign of the protocol's performance, and it is not useful as long as the PDR is good.
VANET metrics	Update Delay or Packet inter-arrival time	This metric is very used to evaluate MAC effectiveness under DCC mechanisms. It is exclusively related to periodic traffic (CAM) to define the average time between two consecutive successfully received packets from the same sender. Thus, it can be used to calculate the probability that this average time exceeded a certain threshold.
	Packet Delivery Ratio	This metric has a relation with the reception rate of broadcast traffic which depends usually on the mutual distance between transmitter and receivers where the broadcast traffic sources are uniformly distributed and without retransmission. There are two types of the PDR, it can be in a Region of Interest (ROI) when considering the effect of geo-forwarding, or restricted to certain areas like the center of the crossroads where the risk of hidden terminals.

VANET metrics	Cover Ratio (CR)	CR is defined as the total periods when a receiver can actually receive consecutive packets from the same sender within a certain predefined time interval and a predefined distance, divided by the total periods when the receiver is expected to receive from the sender within the same predefined distance.
	Discovery range	The discovery range is defined as the longest distance between a transmitter and a receiver which is able to receive packets with a given reception rate. The ideal discovery range should have the highest number of discovered devices and remains constant when the density increases.
	(Max-min-)Fairness	Ratio between maximum and minimum of the number of channel access opportunities among all stations during a period of time
	Distance of Simultaneous Transmissions	This is very interesting metric for periodic broadcast traffics, it can reflect the spatial multiplexing and it is related to the PDR metric. It can show the impact of re-iterated collisions.
	Causes for Simultaneous Transmissions	It is exclusively used for CSMA/CA evaluation. Transmission collision is happened when at least two senders transmit at the same time and this is because of several reasons: same back-off, simultaneous count-down or hidden to each others.
Channel metrics	Channel Load or Average channel busy ratio (CBR)	This represents the occupancy of the channel as a percentage of time, it is used especially for DCC. In CSMA/CA the number of collisions becomes significant when the Channel load exceed 60 % and the Update Delay complicates the situation. It is the Average of CBR values of all stations in the network for a given period of time.

3.5 Conclusion

Standardization plays a crucial role in facilitating adoption of a technology while enabling the interoperability between different car manufacturers in different regions from EU, Japan, and the USA. The standardization of vehicular communications is a quite complex and slow process involving several SDO to work closely together towards harmonized standards.

This chapter provides a global overview of a consistent set of important standards to build ITS station units for VANETs and in general for C-ITS. Most important standards of the CEN/ISO/ETSI under the European Commission's mandate M/453 specifying protocols for VANETs with ITS stations and of the IEEE/WAVE family are summarized [93] . They have been published to cover different aspects, e.g., the station and communication architecture, messages, management, access technologies, networking, security, and facilities aspects.

Literature review of MAC technics for VANET

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4.1 Introduction

Vehicle safety applications rely heavily on periodic broadcast of (CAM/BSM) safety messages which are intended to be transmitted up to once every 100 ms. So that vehicle safety applications can meet their latency and accuracy requirements. The current MAC of VANETs, which is IEEE 802.11p, has a heavy responsibility to achieve these requirements. It uses CSMA/CA and a random back-off procedure to reduce collisions of over-the-air frames. However, at high densities of vehicles, the wireless medium can quickly become highly congested and collisions among frame transmissions may occur with high probability which leads to a scalability and reliability problems. Moreover, due to this periodic nature of transmission, each vehicle will start its broadcast transmissions when switched on and, since then, it will keep the generation of messages with the same initial phase. This means also that if the transmissions of two vehicles collide once, they are probably to collide again and again and then a problem of fairness

arises among the vehicles in a VANET. The technical challenges related to the use of IEEE 802.11p MAC in the VANET environment have been discussed in chapter 3. Instead of the standardized enhancement to deal these challenges through DCC, the MAC layer congestion issues still imposed and therefore further improvement still needed. As the main focus of this thesis is to propose scalable and reliable MAC protocols for periodic broadcast of (CAM/BSM) safety messages, it is important to evaluate the existing proposals. For that, this chapter is entirely dedicated to a general review of the research literature related to medium access control in vehicular networks. The selected solutions are classified following the channel access technique they use, and the strengths and weaknesses of each class of protocols are addressed.

This chapter is organized as follows. The section 4.2 provides taxonomy of the main approaches in the literature that have been proposed to solve the MAC layer congestion issues over vehicular networks according to their access mode. The section 4.3 presents a survey of MAC techniques which are based on CSMA/CA of IEEE 802.11p for VANET that have been recently proposed in the literature, as well as their classification according to some criteria. The section 4.4 presents a survey of Synchronous Time-Slotted-based MACs techniques also known as TDMA-like MAC which has been recently proposed as an alternative to the IEEE 802.11p standard. After that a classification is proposed according to some criteria. The section 4.5 discusses the key characteristics of MAC protocol to support the road safety application requirements under Vehicular communications. Finally, the section 4.6 summarizes the chapter.

4.2 Taxonomy of MAC proposals

There are some many different MAC variant and alternatives which have been proposed in order to improve the performance of the current MAC standard (IEEE 802.11p) for VANET. Therefore, taxonomy can help to have a global view and general understanding. However, the classification is never being strictly dischotomic and mixed MAC types can be found in some proposals. Note that, the multi-channel control is not taken in our classification because it is not in the scope of our thesis. In the Figure 4.1 presents the taxonomy proposed to visualize the main types of Mac technics.

1. **Asynchronous CSMA-based MACs** : Instead of the known limitations of CSMA/CA, it becomes the basis of the majority of the proposed asynchronous MAC for VANETs.

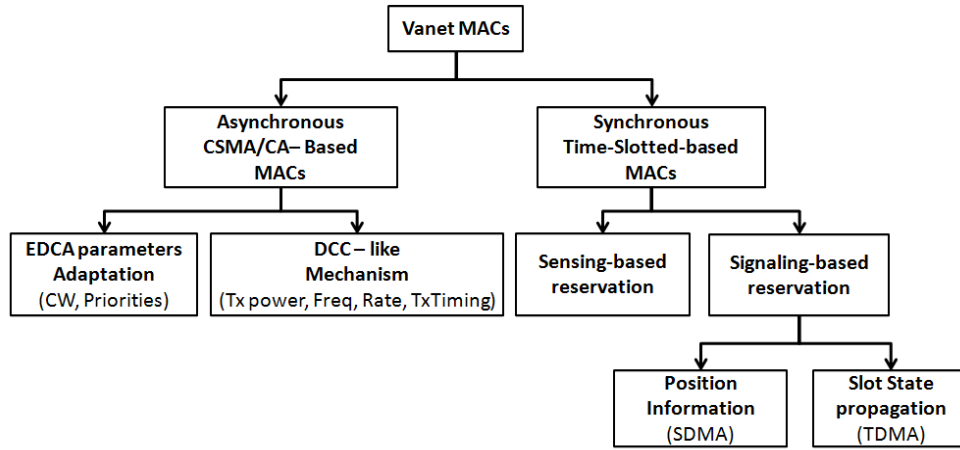


Figure 4.1: Taxonomy of the MAC technics for VANETs.

This is thanks to its simplicity, distributed nature, freedom from central coordinator and effectiveness to deal with mobility and topology changes. However, its weaknesses start to be significant when the channel becomes congested. Therefore, the improvement of CSMA/CA still makes sense. The classification of CSMA/CA-based protocols is performed according to their mechanism which they act on. These mechanisms should base on channel load estimation (local density estimation) and vehicles' coordinate information like speed and position of vehicles and time of packet sending. They can be categorized under two relevant classes which are presented as follows:

- (a) **EDCA parameters Adaptation** : The mechanisms of this category still acting on CSMA/CA parameters (such as Contention Window, priorities, etc.). The researchers working on the medium access issue mention that the CW and the priorities values used in the standard is not optimal. Adapting these values, which can be increased and decreased according to the vehicular density, has a growing tendency in the context of random multiple access control. A number of modified back-off algorithms have been proposed in the literature
- (b) **DCC – like mechanisms** : The objective of this category of MAC is to prevent the congestion on the channel by adapting the transmission parameters such as (1) the transmitted power, (2) the generation rate, (3) the transfer rate, and (4) transmission timing. The European ITS architecture ETSI standard gives the opportunity to adapt these parameters through cross-layer design which have been discussed in Chap. 3.

Note that, the transmission timing control is a promising technique in this category which is not standardized yet. It consists to spread the start of transmission time over the CCH interval to mitigate contention after switching to the CCH channel. However, the best adaptation still an open problem and many solution have been proposed.

2. **Synchronous time-slotted-based MACs** : Another alternative method is to use synchronous time-slotted-based MACs which is also known as Time-Division Multiple Access (TDMA) [11] . It is the most suitable for vehicle communications then the other contention-free mechanism like Frequency Division Multiple Access (FDMA), Code Division Multiple Access (CDMA) [94] and Space Division Multiple Access (SDMA) [95]. The idea of TDMA is to organize the channel access according to time ordering to ensure a contention-free medium access between vehicles. Note that, before the definition of WAVE architecture, synchronization had not sufficiently studied for mobile network. It had been still commonly believed that synchronization was not suitable for VANETs and it will lead to blocking performance due to high mobility of vehicles. However, over the years, synchronicity is already mandated as part of IEEE 1609:4 for channel switching (see chapter 3). It is considered as a standard feature in modern vehicles, to support a critical safety application like BSM [96]. It can be easily achieved in general by Global Navigation Satellite Systems - GNSS where Global Positioning System (GPS) system is the most popular. Synchronization in VANETs under is achieved by the one-pulse-per-second (1PPS) signal method [97]. Some studies have demonstrated that synchronous MAC can be a promising method for VANETs which gives a satisfactory performance [4]. Therefore, synchronous time-slotted-based MACs can reuse the same physical layer as CSMA/CA and co-existence between them can be achieved. Furthermore, the use of a cooperation based slot reservation can have the potential to solve the main issues of CSMA/CA which is the hidden terminals problem. As a matter of fact, all of time-slotted-based MACs adhere to the following concepts: (1) The periodic time frames has to be divided into a fix number of slots; (2) the time frames are separated by guard-times to counteract non-accurate synchronization; (3) All the vehicles follow a common synchronization system; (4) the size of the slot needs to be as long as the longest of the packet to be sent. The main issue for the synchronous

time-slotted-based MACs is the slot reservation. It can be centralized or distributed. Note that this work focuses only on the distributed manner which is based on three approaches:

- **Sensing based reservation** : the slot reservation used in this approach is just based on receiving packets and continuously listening to the channel to identify free slots only in one-hop neighbors.
- **Position based Signaling reservation** : The time slot reservation is organized according to physical location of vehicles known as SDMA [95]. The vehicle's locations need to be broadcasted or the road has to be divided into segments and each one corresponds to a time/slot of a TDMA frame structure.
- **Slot State signaling reservation** : The signaling is based on exchanging slot-related state (Reserved or free) between vehicles in one-hop and may over multi-hops to know whether the node is free or busy thereby solving the hidden node problem. The signaling can be Out-of-Band where the vehicle broadcasts additional packets during a slot reservation phase which contain the slot status to its two-hop neighbours. Generally this packet is called the **Frame Information (FI)** . Otherwise, the In-Band signaling consists of adding header information to the transmitted packet which contains the slot status. By listening to this header, vehicles can detect the free slots.

4.3 Asynchronous CSMA/CA– Based MACs

This section presents a survey of MAC techniques which are based on CSMA/CA of IEEE 802.11p for VANET that have been recently proposed in the literature. After that a classification is proposed according to some criteria.

4.3.1 Survey

Several solutions based on a CSMA-like MAC have been extensively investigated in the literature. They aim to improve the performance of beaconing (periodic broadcast) in the context of vehicular networks. The main proposals are presented as follows:

1. **AdptEDCA [98] , (Adaptive EDCA Mechanism for Vehicular Ad-hoc Network)** : The protocol is an adaptive EDCA mechanism for prioritized applications to improve the per-

formance of vehicular communications. The authors propose a seven access priorities for the EDCA mechanism rather than the four priorities specified in IEEE802.11p standard. For that, they re-classify the vehicular applications to the following three classes: (1) safety of life applications with three access categories; (2) Safety applications with two access categories; and (3) non-safety application with two access categories. Each priority is specifies by its two QoS parameters which are AIFS and CW. The value of these parameters is adapted depending on the density of vehicles through a proposed equation. So that, the first access category of safety of life application has the highest priority and the second access category of non-safety applications has the lowest priority.

2. **PPCA [99], (Performance and Fairness in VANETs)** : The protocol is a simple and effective method called **Periodic Phase Changing Application (PPCA)** aimed for improving the periodic one-hop broadcast by avoiding the main causes of collisions. When the vehicle is switched on, it starts sending periodic packets with a relative phase F which is randomly initialized and constant thereafter. If there are many vehicles in a communication range or hidden to each other, the probability that multiple vehicles have the same F will increase. As a result, the probability that multiple vehicles choose the same random number from a given contention window (CW) interval will increase too, causing high number of collisions (Direct and hidden). The idea of PPCA method is to use simply a variable size of phase F instead of a fixed one, in order to spread the sending starting time of the contending vehicles.
3. **FLB [100] , (Contention Window Adaptation for Broadcast Beaconing in Vehicular Ad Hoc Networks)** : This paper presents a **Fuzzy Logic-based Broadcast MAC Controller (FLB)** responsible for the medium access for broadcast in vehicular networks. The FLB is an intelligent adaptive controller aims to regulate dynamically the size of CW during message broadcasting based on the traffic density. The CW parameter is calculated based on a “nonlinear control law” derived by the construction of the fuzzy logic system. This solution is tested for the four access categories at the same time, as defined by the IEEE 802.11p, by broadcasting a mixture of different types of messages, so as to create more realistic scenarios. This is in contrast to what is found in the literature, where all vehicles used the same contention window settings per simulation run.

4. **DCW [101] , (Modelling and performance analysis of dynamic CW scheme for periodic broadcast in VANET) :** The protocol aims to find a suitable CW size for a better beaconing broadcast performance which to be adapted to the dynamic density in VANET. For that, the authors focus on the packets inter-arrival time criterion (packets update delay) which is one of the import factors to determine the performance of a periodic broadcast. It is strongly influenced by the risk of collisions, the higher the probability of collision, the longer the packet update. Therefore, the best CW size should be the tradeoff between the collision probability and the average packets update delay. The authors propose an improved Markov model to study the broadcast performance for different CW sizes and different vehicle densities where the average packets update delay is chosen as a target function. For a given vehicle density, the CW size corresponding to the minimum average message update delay in T is the best value for the **Dynamic Contention Window (DCW)** scheme. As an example, if the vehicle density is between 20 veh/ km to 80 veh/km, the CW= 16 will be the best choice. However, The CW size can be reduced to 8 when the VANET becomes, sparse, less than 20 veh/km.

5. **RB [102] , (Reverse back-off mechanism for safety vehicular ad hoc networks) :** the **Reverse Back-off (RB)** mechanism is specifically designed for road safety applications with highly congested vehicular networks. Using an analytical framework, the authors study the performance of the back-off mechanism and the role of the contention window on the control channel of a vehicular network. Based on these findings, they conclude that the optimal CW in a VANET must find the correct balance between collided and expired messages. While the former is hard to be detected, the later can be detected with no effort and it can form the basis of a proposed back-off mechanism. Therefore, instead of beginning with a small CW That would be increased after every failed transmission, as in IEEE 802.11 BEB, the reverse back-off mechanism starts with a fairly large initial contention window (CW) and decreases it for every expired beacon. The CW is halved after every expired CAM and it returns to the original value CW define in the standard. A larger contention window than the one proposed in IEEE 802.11p is needed in order to cope with medium and high vehicular densities.

6. **MBA [102] , (A Modified Backoff Algorithm for Safety Message Delivery in IEEE**

802.11p/WAVE Networks) : This paper presents a **Modified Backoff Algorithm (MBA)** for safety message broadcasting in IEEE 802.11p/WAVE networks. It tackles the flash crowd problem for safety messages is incurred by CCHI-SCHI interval switching. The proposed MBA includes two phases: (1) To adjust the contention window size, (2) To generate randomly a non-uniformly distributed backoff timer value. The two phases are executed according to the vehicle's travel information such as location, speed, and direction among the neighboring vehicles and by using mathematical equations.

7. **Geo-backoff [103] , (Bigger is better - combining contention window adaptation with geo-based backoff generation in DSRC networks)** : The main objective in this work is to improve the communication performance in the context of vehicular safety, especially at close ranges, where reliable communication is safety critical and packet collisions are undesirable. According to the analysis performed in this work, the significant amount of simultaneous transmissions are when vehicles choose the same backoff counter, especially in the close vicinity, which is the most critical area with respect to safety. Based on that, the authors introduce a new concept called geobackoff which investigates a combination of an increasing CW and generating the DSRC backoff by exploiting geographical information. So, the proposal implements two countermeasures: First, it increases the Contention Window (CW) to reduce the probability of simultaneous transmissions in general where the backoff generation is based on a uniformly distributed random process and is not able to distinguish between close-by and far-away. Second, it exploits the geographical information for generating the current backoff counter to further reduce the probability of packet collisions at short (critical) ranges. For that it aims to generate different backoff counters for contending vehicles, which are located in the immediate vicinity, by using their current positions.
8. **SBB [104] , (A modified 802.11-based MAC scheme to assure fair access for vehicle-to-roadside communications)** : The paper focuses on fairness problem in vehicular ad hoc networks arisen due to the varying speed of the vehicles. The fact they move with different speed across an access point (AP), they have different residence times in the coverage area of the AP. It implies that accessing the channel independently to the speed of vehicles should not serve them equally and more shared of times are assigned to the vehicles with

low velocities. The authors propose a modified 802.11 DCF channel access scheme called **Speed-Based-Backoff (SBB)** as a solution to the problem. The proposed scheme adjusts the probability of transmission at a time slot for each vehicle according to its speed. To this end, the protocol changes the probability of transmission through changing the minimum contention window size. For this respect, the authors obtain the relations between speed and window size through analytical approximations.

9. **Adapt_EDCA [105] , (Enhancing VANET Performance by Joint Adaptation of Transmission Power and Contention Window Size)** : In this paper, the authors present a new scheme called Adapt_EDCA for dynamic adaptation of transmission power and contention window (CW) size to enhance performance of information dissemination in Vehicular Ad-hoc Networks (VANETs). Based on the mathematical methods proposed, the authors present an algorithm which adapts both transmitted power and CW size occur according to the local vehicle density and the network condition, respectively. The adaptation should be run by individual vehicles periodically to ensure a proper updates of the two parameters. The transmission power is adapted based on the estimated local vehicle density which allows to mitigate the adverse effects of high-transmission power and to increase the duration of the communication link in case of low traffic density for inter vehicle communication. While the CW is adapted according to the instantaneous collision rate in order to enable service differentiation and to ensure the fairness of channel access among vehicles. Moreover, the proposed scheme uses the same four access categories adopted in EDCA mechanism 802.11e for services differentiation to provide QoS for traffic safety messages which are categorized according to their urgency delay requirements.
10. **RES [106] ,(Collision control of periodic safety messages with strict messaging frequency requirements)** : The paper tackles the collision problem related to the periodic safety message broadcasts under the IEEE WAVE/802.11p system. With small contention window sizes stipulated in the 802.11p amendment, the MAC layer cannot serve the huge number of contender vehicles waiting for transmission at the beginning of the control channel (CCH) interval. The paper proposes a novel approach to reducing collisions among BSMs and improves the delivery probability. It works on application-level control of the message transmission phase without MAC layer standard modifications. Moreover, it does not

require frequency transmission adaptation due to the strict messaging frequency requirements for safety applications. The proposed method is called [Random Epoch Selection \(RES\)](#) which performs an evasive maneuver on the application layer to let the periodic applications, such as the BSM transmission to minimize the message collisions that would otherwise hard to be controlled by the MAC layer. It creates its own notion of timing slots, called “epochs, of a certain length that divides the sync interval on the MAC layer. The RES protocol dynamically changes the BSM transmission timing slots (epochs) based on the observed use of the slots, it attempts to use an epoch that is most unlikely to be used by other vehicles. It may happen that several vehicles select the same epoch, so for collision avoidance they perform a backoff at the beginning of the epoch. Once it picks an epoch with a successful transmission, it retains it until some other vehicle is observed to come into it.

11. **CBA [107] , (A Collision-based Beacon rate Adaptation scheme (CBA) for VANETs)**

: This paper propose a congestion control approach called [Collision-based Beacon rate Adaptation \(CBA\)](#) to reduce collision rate and save more bandwidth for the dissemination of periodic safety messages (Beacons). It uses the number of detected collisions as a metric to control the beacon generation frequency and therefore reduce the effect of congestion. The authors believe that adapting the beacon frequency is as important as power control approach for the safety applications; indeed, an adequate beacon rate would provide sufficiently accurate information to vehicles. The basic idea of CBA is that it adapts beacon generation rate dynamically based on the number of collisions detected by each node. The rationale behind our scheme is that collisions are directly correlated with the network state; indeed, congestion is the result of a considerable amount of data exchanged between nodes (exceeding network capacity) which would increase the number of collisions detected by nodes. The CBA congestion control scheme consists of two phases: (1) a detection phase to detect the presence of a congestion; it is based on monitoring the number of collisions in the network nodes; and (2) a regulation phase, started when a congestion is detected, to adapt the beacon rate according to the current local density which is computed using an estimation of the number of neighbors in range. The authors propose an Equation to compute beacon rate according to the channel capacity and the number of neighboring

vehicles.

12. **PTS [108] , (New Adapted Back-off Scheme for Broadcasting on IEEE 1609.4 Control Channel in VANET)** :This paper proposes a novel MAC scheme for broadcasting in IEEE 802.11p/WAVE standard during the CCH periods. It addresses two problems related to the congestion control, the first is the challenge facing the random backoff mechanism and the second is the issue of channel congestion phenomenon following a channel switch (from SCH to CCH). When the vehicle density is high, the probability to have two or more vehicles having the same random back-off increases and results in an increase of collision probability. Just after a channel switch, a large number of WAVE devices are found in a period of above-average channel congestion resulting in an unexpectedly high collision rate, knowing as “start-of-interval contention” problem. This paper presents an approach called **Position-based Transmission time Spreading (PTS)** helping devices to avoid this problem with the aim to decrease the collision probability and increase the packet reception rate. The idea of PTS is to spread the starting of transmission times based on geographical positions of vehicles to give them the opportunity to broadcast their messages with a less pressure and a wide free-air during a fixed time while avoiding the expiry time suppression. Before the beginning of each CCH interval, the vehicles are timely sowed (disseminated) over the CCH interval. Each vehicle is equipped with a sowing calendar containing a mapping between geographic sectors and the corresponding slot numbers which represents the transmission starting times of vehicles. Each node calculates its geographic position using the GPS data. Possessing the sowing calendar, it can find out in which sector it is on and therefore find out in which slot time it can begin its transmission. Each vehicle, before transmitting its message, invokes the backoff procedure with the minimal contention window to minimize the collision probability in the case where two or more vehicles can be located in the same geographic sector. That is caused by a large sector size in which many vehicles can be located, or also by the GPS position errors. The vehicle that uses the standard backoff has to wait a long duration (T_a) before it can transmit its packet. This long duration is no more justified if the packet transmission times are quite well spread over the whole CCH interval. The inter-packets time due to the backoff counter is considered to be a lost time. This time is minimized in our proposed scheme.

13. **SPMA [30] , (On the ability of IEEE 802.11p and STDMA to provide predictable channel access)** : This work proposes [Switching Priority algorithm for Medium Access \(SPMA\)](#) which aims to enhance the performance of CSMA/CA MAC protocols when used for broadcasting CAM messages by elaborating with different parameter settings without altering the original IEEE 802.11p standards. The later provides the possibility to assign different priorities to the data packets, which implies different listening/sensing periods and different backoff times. All data traffic had the highest priority resulting in short initial listening periods, but also few discrete backoff values to choose from. This implies that the probability of collisions occurring due to the fact that several nodes choose the same discrete random backoff value. SPMA tries to mitigate the problem of several consecutive packet drops by introducing an algorithm that changes the priority class on a packet per packet basis depending on if the previous channel Access attempt was successful or not. In 802.11P there are four different priority levels called access categories (AC), i.e., queues. The different ACs have different listening periods and CW settings, P1 is the highest priority and P4 is the lowest. Therefore there are no guarantees of first-in-first-out (FIFO) services for messages that arrive at different nodes with the same priority. This work therefore proposes an algorithm that increases the priority of the current message if the previous message was dropped. All nodes start with the lowest priority, P4 and if a packet was sent successfully with these values the node will maintain its priority. Otherwise the next packet will get a higher priority, as long as the packets are dropped until reaching the highest priority P1. Once the node experience a successful transmission, the next packet will again get the lowest priority, P4.
14. **CEB [109] , (A self-adaptive back-off optimization scheme based on beacons probability prediction for vehicle ad-hoc networks)** : This paper proposes a new back-off algorithm called [Collision-Expiration Back-off \(CEB\)](#) algorithm with the aim of improving the broadcast reception rates for beacon messages. As a first step and in order to have a better understanding of the performance of beacon messages, the authors propose Markov chain model to investigate the relationship between collision probability, expiration probability and the minimum CW. Based on that, The CEB is proposed with the following method: Each vehicle adjusts the value of its own contention window according to the relatively

size between the local number of expired messages (E_i) during CCH interval and a preset threshold (E_0). The preset threshold E_0 represents a reasonable value of expired messages acquired through the analytic study and a set of simulations. The CEB assumes that if E_i is smaller than E_0 , then the lost packets in VANETs are due to collision, otherwise, is due to expiration. Note that the local number of expired messages is calculated collaboratively, each vehicle exchange an information about the expiring of its current beacon through a field in the MAC header.

15. **DTB-MAC [110], (A reliable token-based MAC protocol for V2V communication in urban VANET)** : This paper proposes a low-overhead token-based MAC protocol, which is called **Dynamic Token-Based MAC protocol (DTB-MAC)** . It combines random access with a token passing technique. The token ring approach can be implemented on top of IEEE 802.11p to offer QoS provisioning in terms of reserved bandwidth and bounded delay when operating under high densities. Hence, DTB-MAC acts as a random access MAC scheme at low node density, while it successfully deploys the token passing method at high node densities. DTB-MAC is decentralized protocol, not requiring synchronization or any extra overhead for control traffic while still using standard IEEE 802.11p hardware. Vehicles that temporarily reside in each other's vicinity form different groups (rings), and they try to keep the token circulating between ring members as much as possible to clarify who has the privilege to access the channel. The node holding the token transmits its beacon and selects another ring member as the token holder by accounting for its transmission urgency, measured as time proximity to the beacon delivery deadline for that node. During that process, other ring members remain merely listening to beacon transmissions to find out when their turns to transmit beacons takes place; this is detected based on the received token data, which is piggybacked on the beacon itself.
16. **LIMERIC [111] , (a linear message rate control algorithm for vehicular DSRC systems)** : This paper defines a new linear message rate congestion control algorithm named **Linear Message Rate Integrated Control (LIMERIC)**, which is designed for DSRC V2V safety communication exclusively for beaconing. LIMERIC falls in the category of Adaptive DCC Algorithms which act on the difference between the measured CBR and a CBR target (CBR error signal). The CBR target is calculated through a mathematical study. LIMERIC is

a distributed algorithm, executed independently by each vehicle in a neighborhood and it works on simplified network where all vehicles can measure the same channel load. Each vehicle can adapt its own message rate linearly according to the entire CBR error in order to drive the CBR toward a given limit (the CBR target value), so LIMERIC aims to achieve fairness such that all the network converge toward the same aggregate message rate goal. It provides a significant improvement over the limit cycle convergence behavior inherent in traditional binary control algorithms.

17. **VAR [112] , (VANET Adaptive Beaconing Based on Fuzzy Logic) :** The paper proposes an intelligent scheme called **VANET Adaptive Beaconing based on fuzzy Logic (VAB)** that adjusts beacon rate based on fuzzy logic. The system uses three factors for the adjustment which are channel busy time (CBT), mobility and packet delivery ratio (PDR). These factors are taken as inputs to generate the congestion rank as an output. Based on this congestion ranking produced by the fuzzy logic system and the current beacon rate (CBR) the next beacon rate (NBR) is determined by the rate control mechanism. The VAR protocol's performance is evaluated in both highway and urban environments
18. **RPC [113] , (Adaptive intervehicle communication control for cooperative safety systems) :** This article proposes a **Rate-Power Control (RPC)** algorithm that describes how beacons of a vehicle should be broadcast to its neighbors based on the dynamics of a vehicular network and safety-driven tracking process. The Rate control decides how frequently a subject vehicle should broadcast its own beacon while Power control decides how far the state information. For the Transmission Rate Control, at every CCH interval, each vehicle j calculates its transmission probability p based on suspected tracking error $e(j)$ on neighboring vehicles toward its own position in a Euclidean sense. If suspected error $e(j)$ is smaller than E (the error threshold), there is no transmission at all from vehicle j . This threshold design leaves the channel to be used by other vehicles when the suspected error of vehicle j is within the tolerable range. Otherwise, if the suspected error is larger than this threshold, the probability of transmission in that time step t is computed according to a specific equation. For the Transmission Power Control, the transmission range $L(t)$ is adjusted based on the observed channel status. The authors propose a simple design to scale transmission range linearly with average channel occupancy. This method is scalable

and easy to implement. The Average channel occupancy U is a real number between 0 and 1. It is computed for each vehicle by observing the clear channel assessment (CCA) reports that are available from the PHY to the MAC layer of 802.11.

19. **RBRC [114] , (Risk controlled beacon transmission in v2v communications)** : This paper proposes a priority-based adaptive beaconing protocol at the MAC layer for vehicle communications that gives a higher beacon rate for high risk vehicles. The proposal is called **Risk-based Beacon Rate Control Protocol (RBRC)**, it dynamically adjusts the beacon transmission rate (r_{beacon}) for each vehicle, depending on the risk that this vehicle poses to the surrounding vehicles. This risk is computed based on the vehicle's movement, the time and the probability that a vehicle has of colliding with nearby vehicles. The total time for a vehicle to collide with another is denoted as (t_{coll}) which can be broken into three parts. (1) the communications system time (t_s) required for a car to communicate with surrounding vehicles, (2) the reaction time (t_{React}) required for a car to make a decision on future actions, and (3) the braking interval (t_{brake}), the amount of time that the vehicle requires to slow down or take evasive action. Vehicles that have a larger t_{coll} transmit at a lower beacon rate and vice-versa. This reduces the likelihood of channel congestion for high priority vehicles - those judged to be more likely at risk. The scheme determines a higher beacon transmission rate for vehicles between 1 and 20 Hz and the evaluation study prove that it can lead to significant improvements in PDR and network performance, while also improving the safety for each vehicle. Based on these results, the authors recommend that 20 Hz adaptive rate protocol be included as a part of future standards.
20. **ABGR [115] , (Reliable congestion control mechanism for safety applications in urban VANETs)** : This paper proposes an **Adaptive Beacon Generation Rate (ABGR)** congestion control mechanism with the aim of reducing the channel congestion and contention. ABGR can dynamically adjust the beacon generation rate according to varying levels of vehicles' density to ensure reliable and timely delivery of beacons. Based on the correlation between traffic density and vehicle speed, a dynamic application level reliability assessment scheme (T-Pro) is proposed to evaluate application-level reliability of various safety applications with different traffic densities. The adjustment of beacon generation rate is according to

different levels of network density. First, each of the surrounding vehicles can be identified by the vehicle identification information or DSRC device address information which is encapsulated in beacons. In this way, the onboard density calculation module can count the number of surrounding vehicles by identifying the beacon that is received during the unit time period. Then, the current vehicles' density can be obtained by a vehicle. Second, the current vehicles' density is compared with the density threshold. If the current vehicles' density is lower than the density threshold, the beacon generation rate is set to a pre-defined maximum generation rate; otherwise, the beacon generation rate will automatically reduce (increase) when the current vehicle's density increases (decreases). It is noted that the beacon generation rate will not decrease when it is reduced to a certain value. At this moment, the density of vehicles has become so large that road is entirely congested and the minimum beacon generation rate is sufficient for communication among vehicles.

21. **DCAP [116] , (A Density-Based Congestion Avoidance Protocol for Strict Beacons Requirements in VANETs) :** In this paper, a [Density-based Congestion Avoidance Protocol \(DCAP\)](#) is proposed to prevent beacon broadcast storm occurrence. A vehicle running DCAP must predict its own position with a module based on laws of kinematics and another based on Kalman filter. Since a GPS device may present noisy measurements, we employ a Kalman filter to reduce prediction error, and thus increasing accuracy. When the error between predictions made by these modules is above a threshold then a new beacon should be generated. If this error is below the threshold then transmitting a beacon is not necessary. When a neighbor does not receive a beacon from the target vehicle during a time interval, then it will predict their position using the module based on laws of kinematics. The prediction error threshold is determined based on current traffic condition, estimated through local vehicle density. This mechanism can reduce beaconing rate considerably while still ensuring coverage, showing that our protocol can be used for safety-related applications.
22. **BMSF [117], (An optimized MAC Protocol for Safety Messages Broadcasting in VANETs)** : this paper proposes an optimized MAC broadcasting method called [Broadcast Mechanism For Safety Messages \(BMSF\)](#) for the coexistence of beacon messages and emergency

messages and to solve the transmission competition problem between the two kind of messages. It considers channel access back-off mechanism using one-dimensional (1-D) saturated Markov chain model to describe back-off mechanism of safety message broadcasting. And it also uses a message generating rate self-adaptive control method for beacon messages to solve the channel congestion problem caused by high traffic density in VANETs. The proposal algorithm uses the CBR, as an evaluation parameter that can directly reflect the channel load state, to optimise the back-off mechanism and adapt the beacon generating rate.

4.3.2 Classification

The previous section presents different protocols based on a CSMA-like MAC which aims to improve the transmission efficiency by adapting the Transmission Parameters of the IEEE WAVE/802.11p standard. This section gives a classification of the proposed protocols according the transmission parameters presented as follows:

- **CW adaptation and Access Priority** : They are the two principle parameters of the EDCA which is distributed channel access scheme used of vehicular communication.
- **Packet Rate** : Or beaconing rate adaptation is used also to reduce the number of transmitted safety messages in a dense network, speculating the relationship between high density and reduced speed in vehicular traffic.
- **Tx power** : The transmission power control has an important impact on the number of hidden nodes which can increase the spatial reuse, and hence the channel capacity, in a congested network.
- **Tx Timing** : Spreading the transmission access time over the CCH is one of the attractive parameter used to avoid congestion in the channel.

The final parameter is the Data rate adjusting where the increased data rates can be achieved by using more complex modulations and result in a lower occupancy of the CCH. This parameter is not commonly used for the vehicle communication because of its complexity. Therefore, the present thesis does not study any approach focused on this parameter. The adaptation is based on some parameters which are: the local density estimation, the CBR,

vehicles' coordination (position and speed), beacons collision/expiration detection and local beacon expiration estimation. The goal is to increase the efficiency of IEEE 802.11p broadcasts communications. The Table 4.1 shows a classification of the proposal approaches presented in the previous section according the transmission parameters and the adaptation parameters

Table 4.1: classification of CSMA-like MAC protocols

Protocols	Adaptation Parameters						Transmission Parameters				
	Beacon Collision Detection	Beacon Expiration Detection	Local Beacon Expiration Estimation	Local Density Estimation / CBR	Vehicles' Coordinate Information		CW Adaptation	Access Priority	Tx Timing	Tx Power	Packet Tx Frequency
					Position	Speed					
PPCA [99]									X		
AdptEDCA [98]				X			X	X			
FLB [100]				X			X				
DCW [101]				X			X				
MBA [110][118]				X			X				
Geo-backoff [103]					X		X				
SBB [104]						X	X				
RB [102]		X					X				
Adapt-EDCA [105]				X			X	X		X	
RES [106]									X		
CBA [107]				X							X
PTS [108]					X	X	X		X		
SPMA [30]	X							X			
CEB [109]			X				X				
DTB-MAC [110]									X		
LIMERIC [111]				X							X
VAR [112]				X							X
RPC [113]				X	X					X	X
RBRC [114]					X	X					X
ABGR [115]				X		X					X
DCAP [116]				X							X
BMSF [117]				X			X				X

4.4 Synchronous Time-Slotted-based MACs

This part presents a survey of Synchronous Time-Slotted-based MACs techniques also known as TDMA-like MAC which has been recently proposed as an alternative to the IEEE 802.11p standard. After that a classification is proposed according to some criteria.

4.4.1 Survey

Due to the inherent drawback of CSMA access scheme, there have been many works considering time division multiple access (TDMA). Various TDMA-like MAC protocols have been proposed in the literature for inter-vehicle communications. They can be classified in two categories: cluster-based slot assignment and decentralized-based slot assignment schemes. The former class does not count many popular solutions [119], [120], [121], [122], [122], [123], [124] and has been somehow dismissed. The common idea which they work around is the dynamic and distributed creation of clusters for the optimal and scalable management of assignment and re-use of the transmission slots. However, the idea of creating clusters before slot reservation is considered today too challenging and critical in a very dynamic environment like VANETs. On the other hand, the decentralized-based slot assignment schemes are totally distributed without any central control is needed. The vehicles exchange the slot status information with in-band or out-of-band manner to coordinate the usage of time slots (assignment and re-use). Some works focuses on improving the performance of this category of TDMA-like MAC. For example in [125] the authors introduce a dynamic control of the transmission range to improve the efficiency of TDMA-based scheme in VANET. In [126] the paper tackle mobility-caused time slot collision, time slot shortage, and beacon rate limitation issues by using several technics among of them machine learning method. In [127] the authors propose a technique to deal with slot collisions, so that Instead of waiting for another time interval, nodes select other idle slots to access directly during the current time interval once they sense that there are other nodes trying to access the current slots.

This survey focuses only on slot assignment technics under the decentralized-based TDMA scheme. The most popular proposals are presented as follows:

1. ADHOC-MAC [18], (**ADHOC MAC: New MAC Architecture for Ad Hoc Networks Providing Efficient and Reliable Point-to-Point and Broadcast**): This paper presents a [MAC](#)

protocol for ad hoc networks (ADHOC-MAC) which is able to overcome hidden and exposed terminal problems in inter-vehicle communications. The protocol is based on a dynamic TDMA in which a broadcast signaling channel is set up, in a completely distributed way, by the RR-ALOHA procedure which is part of ADHOC-MAC. With this, all the vehicles can know about the activities of their two hop neighbors and can thus avoid collisions. The ADHOC-MAC protocol suppose that the ad hoc network is devised to an environment in which the terminals can be grouped automatically in the physical layer into clusters in such a way that all the terminals of a cluster are interconnected by broadcast radio communication. Such a cluster is defined as OneHop (OH), and it is assumed that the terminals belonging to different clusters (disjoint clusters) cannot communicate with each other at the physical layer. Note that terminals can belong to more than one OH-cluster, leading to the case of non disjoint clusters. The union of OH-clusters having a common subset is called a Two-Hop (TH) cluster. Every terminal must, in order to become active, acquire a slot in the frame of N slots, to be correctly heard by all the terminals within the same OH-cluster. Each vehicle listens to the channel at least during one frame and randomly selects a time slot as its basic slot. During its transmission slot, each vehicle transmits a packet containing FI, that is a vector with N entries specifying the status of each of the preceding N slots, as observed by the vehicle itself. The slot status can be either BUSY or FREE: if a packet has been correctly received or transmitted by the station it is BUSY, otherwise it is FREE. The transmission is successful if the slot is coded as "BUSY by all the received FIs; otherwise the transmission has failed and the selection process will be repeated. In the case of a BUSY slot the FI also contains the identity of the transmitting terminal. Based on received FIs, each terminal marks a slot as RESERVED or AVAILABLE. Note that the transmission of terminals belonging to disjoint OH-clusters cannot collide at any terminal they reach, therefore the slots can be reused.

2. ASDM [128], (**A reliable link-layer protocol for robust and scalable intervehicle communications**): This paper describes a protocol called [Adaptive Space-Division Multiplexing \(ASDM\)](#) with novel features which describe an extension of the explicit SDMA with novel features. Not like the previous SDMA protocols, the ASDM is capable to adjust automatically the time slot allocation in response to changes in vehicle densities without exchanging

control messages and using infrastructure. The slot allocation in SDMA approaches consist of dividing the roadway into cells that can contain at most one vehicle using a mapping function that maps cells to time slots, and assignment rules that specify which of these time slots a vehicle is authorized to be used. The primary goal of the mapping function is to ensure that the time slots assigned to a vehicle are as evenly distributed as possible without any infrastructure. It is defined as the mathematical function that assigns each of these cells a unique time slot. Moreover, it reuses time slot assignments subject to the constraint that no two cells within a predefined range of each other be mapped to the same time slot. The assignment rule in ASDM supposes that vehicles may transmit in the time slot assigned to the cells that they occupy. Therefore, each vehicle is able to obtain its GPS position information and also the positions of the preceding vehicles through the receipt of periodic messages from each other. A vehicle could accurately determine its own position with a combination of GPS and the positions of the neighbor vehicles. This method is easy to implement in highway scenes. However, the topology of the roads is complex, and it is difficult to divide roads into segments under the city scenarios. Meanwhile, it decreases the collision rate at the cost of an increased calculation.

3. **VeSOMAC [19], (Self-Configuring TDMA Protocols for Enhancing Vehicle Safety With DSRC Based Vehicle-to-Vehicle Communications):** This paper presents a Medium Access Control protocol for Called **Vehicular Self-Organizing MAC (VeSOMAC)** protocol for distributed TDMA allocation in inter vehicular wireless networking. VeSOMAC self-organization is achieved using a novel in-band signaling technique. Since there is no contention based operation in the protocol, it is collision free at steady state. Also, unlike the existing distributed TDMA mechanisms, by avoiding out-of-band explicit signaling VeSOMAC provides faster reallocation, which is particularly suitable for vehicular applications with frequently changing network topologies. This allocation autonomy, coupled with a novel bitmap vector is used in packet headers for exchanging relative slot timing information across the 1-hop and 2-hop neighbor vehicles. VeSOMAC is designed to be vehicle location and movement aware so that the MAC slots in a highway platoon are time ordered based on the vehicles' locations. Thus, allows VeSOMAC to perform fast slot reconfiguration after topology changes in dynamic scenarios such as highway platoon

mergers, vehicle passing, and other urban traffic situations. The newly joined vehicle analyses the bitmap vector of any received packet and chooses a non-feasible slot that lies on the right side of the slot of the vehicle immediately ahead in the platoon. The chosen slot is based on the frames of the existing vehicles. Upon choosing a slot, the vehicle starts transmitting data periodically once per frame. Packet collisions in VeSOMAC are detected using implicit acknowledgements through the bitmaps. From the bitmaps transmitted by all its neighbors, a vehicle can infer if all those neighbors have successfully received its own transmission. If not, the vehicle concludes that its transmission got either corrupted, or lost due to a collision.

4. MS-Aloha [129], (**Mobile Slotted Aloha for Vanets**): is a synchronous slotted TDMA-based MAC protocol specifically designed for VANET. In *Mobile Slotted Aloha for Vanets (MS-Aloha)*, all the vehicles broadcast a CAM message in their predetermined timeslots (TSs). This message will be periodically propagated to only their one-hop neighbors per frame, which means each vehicle must choose a TS in every frame beforehand. Roadside units (RSUs) are not used in MS-Aloha. Only one transceiver is assumed to be equipped with each vehicle. All the vehicles are supposed to share a common synchronous source such as GPS to achieve the synchronization for TDMA. Every vehicle judges the usage (free, busy, collision) of each TS on the receptions of packets in the TSs and appends an exhaustive list of the judgment results in the Frame Informations (FIs) to every packet in its own TS. Since there are N TSs in each frame, there are also N FIs in each TS to describe the usages of N TSs. FI consists of three subfields of Source Temporary Identifier (STI), Priority Status Field (PSF) and State. STI is an identifier of the vehicle occupying the corresponding TS. PSF shows a priority of the occupation of the TS. State shows the state of the occupied TS (free, busy, collision) and it has two bits. In MS-Aloha, there is not a dedicated set-up phase: a vehicle just transmits in a free slot, selected randomly, and checks if it works by controlling the other nodes' feedback; the reservation fades after one period. The purpose of FI is to propagate the network information of TS usage over three hops. FIs provide redundant and diversified information on the state of each TS in order to avoid collision caused by unintentional TS reuse and allows the reuse of TS only after a three hops.

5. STDMA [130], (**Scalability issues of the MAC methods STDMA and CSMA/CA of IEEE 802.11p When Used in VANETs**) : The [Self-organizing Time Division Multiple Access \(STDMA\)](#) scheme is a decentralized MAC scheme which is already in commercial use in a system called automatic identification system (AIS), where it focuses on collision avoidance between ships [131]. The algorithm requires that all nodes in the network regularly send messages containing information about their own position. In [130] the authors evaluate the efficiency of the STDMA for periodic messages (CAM) when used in the context of vehicle safety applications. When a vehicle is turned on, it will follow four different phases; initialization, network entry, first frame, and continuous operation. During the initialization, the vehicle will listen for the channel activity during one frame to determine the existing slot assignments, i.e., listen to the messages sent in each slot, which contains the sending vehicle's position and future slot assignment. In the network entry phase, the node determines its own slot assignment. In The network entry phase, the station determines its own slots to use for transmission of position messages within each frame. If all slots are occupied, the node will select an occupied slot based on its knowledge of positions, namely the slot used by the vehicle located furthest away from itself. This Way channel access is always granted and the distance between two concurrently transmitting vehicle is maximized. When all slots within one frame duration are selected the station will enter the continuous operation phase, using the slots decided during the first frame phase for transmission. However, during the first frame phase, the vehicle will also draw a random integer for each slot which determines for how many consecutive frames the slot will be used. This procedure of changing slots is used to deal with network changes and to avoid transmission collisions when two nodes that use the same slot which were not in radio range of each other and could now have come closer and will then interfere. Note that, the synchronization among the vehicle is done through a global navigation satellite system such as GPS or Galileo.
6. VeMAC [132], (**VeMAC: A TDMA-based MAC protocol for reliable broadcast in VANETs**): it is a novel multichannel TDMA protocol developed based on ADHOC MAC [18] and designed specifically for vehiclare communication. The protocol provides a one-hop broadcast service as well as a multi-hop broadcast service to disseminate information

all over the network. The VeMAC assigns disjoint sets of time slots to vehicles moving in opposite directions and to RSUs, and hence can decrease the rate of transmission collision on the control channel caused by node mobility. The VeMAC employs an in-band signaling techniques for the nodes to access the available time slots and to detect transmission collisions different from the ones used by ADHOC MAC. In the VeMAC protocol, each node must acquire exactly one time slot in a frame per channel. Node synchronization is achieved using GPS which is also employed to determine the moving direction of each vehicle. Each frame is divided into three separate sets of time slots: L and R for those nodes moving on the left and right direction (or downwards/upwards) and S for those communicating with roadside units. Since the focus here is on vehicular-to-vehicular communication, the latter set will be omitted, focusing on the L and R time slots only. When a node x is just powered on and needs to acquire a time slot, it starts listening to the channel for one frame. So then it can determine the time slot used by each of its two-hop neighbours by analyzing the Frame information announces in their packets. Then it attempts to acquire a time slot by randomly accessing any of free time slot. If at least one of the two hop neighborhood simultaneously attempts to acquire the same time slot, then an access collision happens. it repeats the same process in the next frames. until it successfully acquires a time slot. Once it acquires a time slot, it keeps accessing the same slot in all subsequent frames on channel unless a transmission collision is detected.

7. HER-MAC [133], (**HER-MAC: A hybrid efficient and reliable MAC for vehicular ad hoc networks**): It is a contention free multichannel MAC which performs adaptive broadcasting. It is assumed that each vehicle has a half-duplex transceiver to transmit safety/alert messages in the CCH without collision. Each Sync Interval (SI) in CCH is split into Reservation period (RP) and contention period (CP). RP contains emergency slots (Emgslots) for communicating emergency messages. The number of EmgSlots in the RP is dynamically adjusted according to the number of vehicle nodes in the two-hop range of the reference node. The CP is used for the vehicle node to reserve an EmgSlot or to exchange control messages (WSA). [Hybrid Efficient and Reliable MAC for vehicular ad hoc networks HER-MAC \(HER-MAC\)](#) requires high level of coordination during broadcast of messages. Each node has to maintain a Frame Information Map (FIM) to store the status of EmgSlots oc-

cupied by all neighbor nodes. Each EmgSlot in the FIM can be empty or occupied (marked as "1" or a node ID). When a new vehicle node joins the network, it has to listen the whole RP to collect the status of all EmgSlots of its two-hop neighbors. Then, it tries to send a Hello message in the CP to reserve the next available EmgSlot after the last EmgSlot occupied by its two-hop neighbor node. Due to the changing topology, some EmgSlots will be empty. In order to keep the minimum length of the RP, the node which occupies the last EmgSlot will switch to another available EmgSlot before its current EmgSlot by sending a Switch message. An access collision happens when two or more vehicle nodes in the two-hop range of each other try to reserve the same EmgSlot. It can be detected if at least one of its one-hop neighbor nodes confirm about its EmgSlot reservation. In that case, that vehicle node has to reserve the EmgSlot again until all one-hop neighbor nodes confirms about its EmgSlot reservation.

8. CS-TDMA [134], (**scalable CSMA and self-organizing TDMA MAC for IEEE 802.11 p/1609. x in VANETs**): It is a multichannel MAC protocol for VANET called a **Scalable CSMA and Self-Organizing TDMA MAC (CS-TDMA)** which consider the channel access scheduling and channel switching. The protocol defines a concept of "Chip" for the control channel. It is composed of a transmission (TS) period and reservation (RS) period. The TS period is TDMA based, which contains a sequence of time slots denoted (T) hat is used for transmission of safety messages and control messages. It can be accessed only via reservations. The RS period is CSMA based, which is used for new (T) reservations, or transmissions of high priority safety messages. For safety concerns, each vehicle must acquire at least one time slot on the TS period to broadcast safety messages and control messages on the CCH. All the transmissions must carry the current number of TS slots (N) and other information for accomplishing the protocol, namely the Chip Information (CI). In CS-TDMA MAC, the service area is divided into a set of region units that are named as clusters. The size of a cluster is adjusted such that all vehicles in the same cluster are able to hear from each other. The cluster size is assumed to the same as the communication range R. Each cluster covers a limited number of vehicles for channel contention and must be associates with a set of non-overlapping frequency subcarriers. Suppose a vehicle (x) powers on or is newly entering a cluster, it needs to acquire a time slot (T1) in the CCH. It

starts listening to the channel for one complete synchronization period. Through analyzing the chip information (CI) of the received messages, the vehicle (x) determines the corresponding reservation map. Similarly, other vehicles that need to reserve a time slot will also transmit the Hello-New messages on the RS period. The vehicles within the cluster will update their CI based on the received Hello-New messages and time slots arrangement for each node. The arrangement sequence is set according to the MAC address of each node. For example, the node with the smallest MAC address will be assigned the first time slot. It will listen for another Chip interval to determine whether the reservation is successful. If no other vehicles access channel in the RS period at the same time as vehicle (x), then other vehicles in the cluster can receive the reservation request from vehicle x and increment the (N), put the ID of vehicle x to the time slot reservation set to update the CI and start broadcasting in the next chip. Otherwise, it repeats the reservation process. To handle the vehicles when they leave the cluster, a slot time re-arrangement strategy is proposed. If a vehicle that occupies a certain time slot is inactive to other vehicles in the cluster for (q) consecutive chips, the vehicle is considered to be out of the cluster set. Then the T slot will be available to other vehicles.

9. RTOB [135], (**RTOB: A TDMA-based MAC protocol to achieve high reliability of one-hop broadcast in VANET**): this paper proposes a slotted TDMA-based MAC protocol named **Reliable TDMA-based One-hop Broadcast (RTOB)**. It inherits the advantages of MS-Aloha and greatly improves the reliability of one-hop broadcast by enhancing the efficiency of channel utilization. This high efficiency is achieved by three proposed principles: (1) Higher spatial transmission slot (TS) reuse where every TS will be reused at intervals of four-hop, rather than just three. (2) Multiple frames reference for the judgment on the use of the TS: In MS-Aloha, a new TS used for a broadcast is decided every frame by referring to FIs of only the last frame. In RTOB, on the other hand, this decision will be carried out every several frames by referring to FIs of the last several frames. Thus the probability becomes lower for the case where a TS is actually used but it is mistaken as “free”, caused by temporal decrease in the received signal strength. (3) Efficient TS reallocation: In MS-Aloha, any two vehicles VA and VB using the same TS cannot recognize each other only if they send at the same time. In RTOB, to cope with this restriction, Collision Notification

is always broadcast by a third vehicle. If this third vehicle V_C can know that V_A , B and V are using the same TS before their actual packet collision and that they are likely to make collision soon, V_C can inform V_b and V_a of this potential collision using a special value add in the packet.

10. CTMAC [96], (**CTMAC: A Cooperative TDMA MAC in Vehicular Ad Hoc Networks**):

This paper proposes a **Cooperative TDMA MAC (CTMAC)** which is a reliable MAC protocol for a fully distributed Vehicular Ad-Hoc Network (VANET) using the slot states sharing scheme. The scheduling policy of DTMAC is to assign itself to one of the corresponding slots to the area randomly achieved more efficient and higher slot utilization through location- based scheduling and fully distributed operation. By the proposed CTMAC, a vehicle detects the carrier signal for each time slot and collects the status. Then, the collected status information is embedded to the MAC header by allocating 1 bit for each slot, and broadcasts it. The vehicle that receives the packet knows the channel state of their neighbors and selects the slot that returns the quickest among the slots that can avoid interference to the channel and transmits the packet. The main ideas here are sharing the sensed slot states and prioritizing slots through the collected slot states from neighbors during a frame with its own sensed slot states without any owner's information of the slots such as ID addresses. Each time slot in CTMAC is divided into two CWs (CW1 and CW2), a Slot Information (SI) header, and the payload which is specified by DSRC as safety applications. SI consists of 92 SSI (Slot State), and 1 bit is allocated to each SSI to store the state information of SI. The vehicle senses a carrier signal every time slot to determine the slot state, which is divided into three states. The first is that the packet is received correctly, and the second is when the packet is being received but the packet cannot be decoded due to signal interference such as packet collision or attenuation. Third, there is no signal received or the signal-to interference-plus-noise ratio (SINR) is too low to receive the packet at all, which is the case when the channel is idle. In CTMAC, 0 is inserted in SSI if the channel is noisy or idle in the i -th slot, and 1 is stored when the packet is successfully received. The size of the SI header is 92 bits according to the number of slots per frame, which occupies 12 bytes of space. When a vehicle receives any packet from another vehicle, it calculates each slot state by using all ratios according to

the distance between each sender and itself over a frame. The vehicles prioritize all slots at each time slot, by considering two values simultaneously. The first value has been received and accumulated during a frame. The vehicle uses that value and considers information coming from its neighbors. V_i is the value obtained by receiving the channel states of the neighbors for slot i for one frame. The second value is what the vehicle senses at the time slot, which is categorized as busy, noisy, or idle. The calculated value is used as the priority of each slot, the vehicle uses this priority to determine the set of slots to attempt to access. For the slot accessing, the protocol CTMAC uses Algorithm (1) which is the channel access procedure that operates at the beginning of each time slot. When a vehicle is trying to transmit a packet at slot i , it immediately waits for CW1 if it is not the owner of the slot, where CW1 equal to 15 μ s. Then it randomly selects a back-off value r between 0 and 3 in CW2. The vehicle occupying the slot has a higher priority to compete with the non-occupied vehicle and accesses the slot first. We coped with merging collision by mitigating the occurrence of access collisions by competing in this CW2 and competing among the vehicles that already occupied the slot. For the slot allocation process, CTMAC uses Algorithm 2 which works through Algorithm 1. When a packet arrives from the upper layer, at this time, if the value V_s of the slot selected in the previous transmission is less than the predetermined threshold, then it is determined that the last transmitted packet collided so it has to reallocate another slot. The algorithm uses an equation for calculating the value according to the channel congestion.

11. SCMACV [136], (**A Scalable and cooperative MAC protocol for control channel access in VANETs**): In this paper, a [Scalable and Cooperative MAC protocol for control channel access in VANETs \(SCMACV\)](#) is proposed to support the periodic beaconing over the control channel in TDMA MAC for vehicular ad hoc networks. The main concerned aspects in SCMACV are communication reliability and protocol scalability. The communication reliability is guaranteed by cooperative beaconing. When broadcasting a beacon, the node embeds the slot state information into the beacon so that surrounding nodes can determine the availability of each slot. Together with the contention process, collisions can be alleviated. The protocol scalability is achieved by the slot access method and the proactive slot reservation. Considering the potential high node density conditions in

VANETs, the proactive slot reservation policy is applied to prepare plenty of idle slots at any time for new nodes to join the network. In SCMACV, the CCH is shared by TDMA. Each slot contains a distributed interframe space (DIFS), a Contention Window (CW) and a data frame (payload). The slot access method is a contention process where the traditional CSMA/CA or the MCBC proposed in [137] are used. In SCMACV, vehicles have two states: online and offline, at the start of the broadcast process, all vehicles take the offline state where they need to randomly select available slots to access the channel. When a node gains the right to access a slot through contention, it becomes online and can broadcast a beacon that contains the index of its target slot, through which this vehicle intends to access the CCH once more, and a Cooperative Message (CM) to inform the surrounding nodes about the states of the subsequent slots. By parsing the received slot state information, the slot availability can be determined in a cooperative manner for every node. Then both online and offline nodes can simply select an available slot to access the CCH. Online node will continue to broadcast beacons in this way until it loses the contention or encounters a collision. Then it becomes offline. The online nodes take responsibility for the cooperative beaconing and the proactive slot reservation. On the other hand, the slot access method also reduces the average delay by using the smaller beaconing period as the node density is decreasing and reservation always keeps enough idle slots so that more nodes can quickly join the network. When a collision occurs, the sender should be informed of the collision by the surrounding vehicle using the designed collision notification mechanism since the sender cannot detect the collisions caused by itself. Therefore, vehicles that caused the collision will abandon using the target slot.

12. MoMAC [138], (**MoMAC: Mobility-Aware and Collision-Avoidance MAC for Safety Applications in VANETs**): This paper proposes a protocol named **Mobility-aware TDMA MAC (MoMAC)**, which can assign every vehicle a time slot according to the underlying road topology and lane distribution on roads with the consideration of vehicles' mobilities. In MoMAC, different lanes on the same road segment and different road segments at intersections are associated with disjoint time slot sets. Assigning vehicles that are bound to merge, with disjoint time slot sets. The beauty of this design is that each vehicle can easily obtain the collision-avoidance slot assignment as long as the vehicle has a lane-level digital

map and knows its current information of belonging to which road and which lane, which can be easily obtained by all the navigation systems (GPS). To achieve common agreement about the usage of slots among neighboring vehicles, MoMAC uses a fully distributed slot assignment scheme, in which each vehicle selects a free slot according to the received slot-occupying information from neighboring vehicles. Specifically, in addition to application data, each vehicle also broadcasts the information with IDs of its onehop neighboring vehicles and slot indexes used by them. In doing so, transmission collisions can be detected by verifying the consistence of neighboring messages and all vehicles can keep tracking the link state changes in the moving. vehicles are synchronized via the GPS and to control the medium access on the CCH, time is partitioned into frames consisting of a given number S of fixed duration time slots and each second contains an integer number of frames. To access the medium, a node has to gain a vacant time slot in a frame before it can transmit messages. MoMAC adopts the underlying road topology and lane distribution on roads into medium resource allocation. It is practical as the road topology and lane distribution are constant and easily obtained. Furthermore, a vehicle just needs to know which road and which lane it belongs to, which are classification problems rather than a absolute positioning problem. As classifying a GPS location to a specific lane and road segment can tolerate localization errors ranging from meters to hundreds meters. To facilitate time slot assignment in a distributed way, every vehicle needs to maintain the information of its neighboring vehicles in one-hop and two-hop ranges. Neighboring vehicles within the communication range of a vehicle constitute the one-hop set (OHS) of this vehicle. If two OHSs overlap with each other, the union of these two OHSs is referred to as a two-hop set (THS). Obviously, vehicles in the same OHS should select different time slots to transmit messages. Moreover, vehicles in the same THS should also choose distinct time slots for communication in order to overcome the hidden terminal problem. In VANETs, vehicles may converge and diverge from time to time due to different velocities and routes. The collisions of slot assignment would arise when vehicles merge together on the move. Therefore, we need to assign disjoint time slots to those vehicles are bound to merge, which is the key operation of MoMAC. Specifically, the time slot assignment in MoMAC has the following process: (1) The road network is divided into individual road segments and intersections and assign slots for each of them so as to minimize potential collisions caused by

vehicle sets moving together. (2) When vehicles move on a multi-lane road segment, the lane information is used to divide time slot sets. (3) When vehicles are at an intersection, the topology of the intersection, which converged by directional road segments, is used to divide time slot sets. (4) When vehicles enter an intersection from a road segment or leave an intersection to a road segment, the upper two schemes are spliced together according to the geographical connection. In the header of each packet transmitted on the control channel, every transmitting vehicle should include set it neighbors and the time slot used by each one of them. When a vehicle x needs to acquire a time slot, it firstly listens to the channel for S consecutive time slots (not necessarily in the same frame). At the end of the S slots, the vehicle (x) can obtain the information of the free slots by analyzing the headers of the received packets and then randomly choose a slot. After the vehicle (x) transmits at the time slot t , it listens to the feedback from its neighbors to determine whether the attempt to acquire the slot is successful. If it is not the vehicle repeat the process. In addition, in MoMAC, a vehicle (x) needs to actively release its time slot and acquire a new one whenever necessary in order to adapt its real-time road scenarios such as changing a lane and entering or leaving an intersection. Vehicles need to change slot frequently. In this way, merging collisions caused by mobility changes can be greatly reduced.

13. SCMAC [138], (**SCMAC: A Slotted-Contention-Based Media Access Control Protocol for Cooperative Safety in VANETs**): This article introduces a slotted-contention-based time-division multiple access MAC protocol **SCMACV** designed for vehicular networks. There is no need to assign fixed slots to nodes; nodes access the channel only when needed. Different transmission frequencies can be supported as the time is not divided into frames and nodes are not restricted to broadcast one packet per frame. Meanwhile, transmission delay can be minimized as nodes access the channel on time after the generation of the packets. Each time slot is divided into two periods: 1) reservation period (RP) and 2) transmission period (TP) in the protocol. Vehicles compete in the RP to reserves a time slot before the transmission can take place in the TP. Each RP is partitioned into a fixed number of minislots (MSs), Sense and broadcast black-burst during MSs is a combined method that is used in SCMAC to confirm whether vehicles can broadcast the periodic safety message during the TP. The black-burst is an approach of sending an energy burst during a MS

(channel jamming signal) which has been widely used in IEEE 802.11p-based protocols for emergency messages dissemination [139]. By obeying the agreed rules, the black-burst signals can be converted into interactive codes (binary numbers 0 and 1). The time used for the channel contention depends on the density of the network in IEEE 802.11p-based protocols. We denote the state when a node chooses to broadcast black-burst by the binary number (1) and the state when a node chooses to sense the channel by the binary number (0). The protocol aims that only one node chooses to broadcast a packet during the following TP according to the competition result in the RP. To achieve this goal, one principle should be obeyed for all the nodes: once a node x chooses to sense the channel in a certain MS, and the black-burst signal broadcast by other nodes is sensed by x , then, the node x quits the reservation process and keeps silent in the following MSs and TP and reserves other time slots to transmit the packet. Let M denote the number of MSs belonging to the RP. Assume that the vehicles preselect the actions in the MSs before the beginning of the RP. Then, there are 2^M choices for each node. An M -bit binary number is formed from the chosen binary numbers, and it belongs in $[0, 2^M-1]$, only the vehicle whose chosen value is higher reserves the TP successfully. However, Transmission collision still occurs when more than one node chooses the same value, and the chosen value is bigger than the values chosen by the other nodes. Then the process will be repeated in the next slot. Transmission collisions caused by the hidden terminals can be eliminated if vehicles that are not one-hop neighbors to each other but have common one-hop neighbors do not broadcast periodic safety message using the same time slots. Thus, this problem can be eliminated by adopting Spatiotemporal Coordination (STC) which consists to divide the road into segments with fixed length R , where R denotes the communication range, and assign different slots to these segments. It is pre-allocated a TDMA slot. This mechanism offers bounded delay, and also there is no reconfiguration latency due to network topology changes. However, the system requires complete pre-mapping of geographical locations to TDMA slots.

14. CSTD MAC [20] (**CSMA with TDMA-like operation for VANET MAC**): One of the TDMA challenging schemes is the difficulty to allocate time slots appropriately to the contending vehicles in a distributive manner. Some solutions have been proposed, as ADHOC MAC

and VeSOMAC, however, they often results in heavy network control overhead, where they require that the vehicles have to exchange their frame information or list of neighbors. The contribution of this paper includes the design of an in-band signalization, called **CSTD MAC** (CSma TDma MAC) aiming to ensure a good allocation slots with less network overhead. The conducted intensive simulations show that the proposed scheme performs better than CSMA of the IEEE 802.11p by reducing the rate of transmission collision

4.4.2 Classification

This section provides a classification of the typical Synchronous time-slotted-based MACs (TDMA-Like) protocols in VANets which are presented in the previous section. The most important and distinctive point of TDMA-Like is how they manage slot reservations or slot assignment. So the classification of these protocols is basically based on their slot reservation coordination by still keeping the decentralized approach. In literature, three main slot reservation coordination are:

- Sensing: in which vehicles continuously listen to the channel to identify free slots and, when one needs to transmit, it will just pick a free slot and keep it as long as it needs it.
- Slot-state signaling: the information about the status (e.g., empty, busy) of each slot can be shared: this introduces a further distinction since the signaling may span through two modes. The first is out-of-Band signaling where vehicles send control packets during scheduled data slots containing slots' allocation information. Based on this information, a vehicle is able to select a collision-free transmission slot, which is used for subsequent data as well as control packet transmissions. The second is In-Band signaling where slots' allocation information is add to packet header, by listening to this header, vehicles can detect the available slots.
- Position-based protocols: in which TDMA slots are allocated based on a vehicle's instantaneous geographical location, which is pre-allocated a TDMA slot. It can be Local where vehicles exchange their position over one-hop and two-hops without using a slot-location mapping or Global where the system requires complete pre-mapping of geographical locations to TDMA slots.

The proposed classification uses two other criteria which are:

- Slot access mechanism: after selecting a free slot the vehicle can access to that slot Immediate and start sending the safety packet or it has to contend with other vehicles in the surrounding using backoff mechanism.
- Overhead size: the size of slots' allocation information exchanged between vehicles can be light or heavy or totally not available in case of using slot assignment mechanism which is based only on sensing.

The Table 4.2 shows a classification of the existing TDMA-like MACs approaches according the previous parameters.

Table 4.2: classification of TDMA-like MAC protocols.

Protocols	Slot Reservation Coordination					Slot Access Mechanism		Overhead Size		
	Sensing	Position-based Signaling		Slot State Signaling		Immediate	Contention	None	Light	Heavy
		Local GPS	Global Slot /Space Map	Out-of-Band	In-Band					
ADHOC-MAC [18]	X			X		X				X
ASDM [128]		X	X			X				
VeSOMAC [19]		X			X	X			X	
MS-Aloha [129]					X	X				
STDMA [131]	X	X				X		X		
VeMAC [132]	X				X	X				X
HER-MAC [133]	X			X		X				
CS-TDMA [134]	X				X	X				
RTOB [135]					X	X				
SCMACV [136]					X		X			
CTMAC [96]		X			X		X		X	
MoMAC [138]	X	X	X		X					X
SCMAC [138]			X		X		X			
CSTD-MAC [20]		X			X		X		X	

4.5 Discussion

The vehicular MAC protocols in the literature are in two broad categories: contention-based and schedule-based. The contention based approaches have the advantage of not being sensitive to underlying mobility and topology changes.

The CSMA of the standard IEEE 802.11p is the contention-based MAC technique adopted for VANET due to its simplicity, dynamicity where vehicle movements do not impose any re-configuration overhead due to the network topology changes as well as its asynchronous mode. However, this contention-based communication mechanism has a lot of limitations which damage the reliability of safety data transmission in DSRC communication.

In the previous section, several solutions based on a CSMA-like MAC have been extensively investigated in the literature to improve the performance of beaconing in the context of vehicular networks. They investigate the impact of adapting the transmission settings: EDCA parameters such as Contention Window, priorities and DCC-like mechanisms such as the transmitted power, the beacon generation rate, the transfer rate, and transmission timing. This adaptation is based on the traffic density, the channel load and vehicles' coordination, where the goal is to increase the efficiency of IEEE 802.11p broadcasts.

Adapting the CW_{min} parameter is the most attractive approach in the context of a beaconing system. This adaptation may consist in either increasing or decreasing the CW_{min} according to the network density. Researchers that have been working and tackling the backoff issue state that the CW value used in the standard is not optimal. In that regard, a number of modified back-off algorithms have been proposed in the literature. These mechanisms should take into account the optimal contention window size. Increasing the CW size can lead to the beacon expiration problem; in addition, decreasing its size may lead to an increased number of collisions. So, obtaining a good balance between these two issues stills a challenging problem.

Using different channel Access priorities provides the possibility to assign different listening/sensing periods and different backoff times interval to the data packets. It could decrease the collisions occurring due to the fact that several nodes choose the same discrete random backoff value. However, the four different priority levels called access categories (AC) of 802.11p standard could not support a high density of vehicles. Notice that, using an adaptive CW and priority access mechanisms do not completely solve the scalability problem of IEEE 802.11

in vehicular communications. So, to guarantee operation reliability of the DSRC system, the effective DCC-like mechanism should be employed.

The main idea of the DCC-like mechanism is to reduce the load on shared communication channels and to coordinate fair channel access among vehicles in the context of VANET. For that, the congestion control algorithms usually adopt a method of dynamically adjusting one or more DCC transmission parameters.

Adjusting the beacons rate generation is the most obvious solution for controlling the channel load in a congested environment in vehicular networks. It can be achieved in a straightforward manner through cross-layer mechanisms. In a very dense environment, vehicles usually have low speeds and the beaconing frequency could be reduced which is a powerful tool in congestion control. However, such a reduction should be designed carefully because sending less messages can easily have the effect of damaging the performance of safety applications instead of improving it. The consequences of this adjustment on every safety application should be taken into account, because, it is still unclear if all applications could deal with such a reduction. Moreover, the maximum frequency of these messages is still an open research problem, Instead of anticipating a maximum value between 5Hz and 10Hz.

Adjusting Transmission power is another solution can be adopted in order to decrease the congestion on the channel by limiting the number of neighbours vehicles while keeping a connected network. It is one of the most studied techniques among DCC-like mechanisms. It can help reduce interference and increase successful reception probability of nearby vehicles [140]. However, this mechanism has to take in consideration the thresholds for information propagation imposed by safety applications. If one-hop communication couldn't reach this threshold, then multi-hop broadcast needs to be adopted. Therefore, not only the delay is increased, but also the congestion problem is amplified. Additionally, this mechanism would require controlling the transmission radio unit every time which is proved to be very difficult and expansive according to the capacity of the existing IEEE 802.11 devices. Transmission power control can be very efficient in some cases but it cannot be considered as a general solution for VANET communications.

Adjusting the data rate is the third mechanism of DCC which has the philosophy to reduce the transmission time of a message when the vehicular density increases in order to give more stations the chance to access the channel during a beacon period. It consists of speeding up the

transmission time of a beacon by using high data rate at high vehicular densities. This practically means to use the signal modulation which occupies the channel for less time. However, any modulation resulting in a higher data rate, requires also a higher signal-to-noise (SNR) ratio at the receiver in order to be demodulated correctly. In the case of the noisy vehicular channel, The experimental studies indicate that a data rate higher than 6Mbps brings an important decrease in performance and drastically reduces the reception probability, even at small distances from the transmitter [141]. According to these results, data rate adjusting does not seem to be an appropriate solution for congestion control in safety vehicular networks. For that, the survey of this thesis does not study any approach focused on this mechanism.

Transmission timing control consists of spreading the density of transmissions over the CCH interval which is an effective solution to avoid contention on the transmission channel. However, the optimal interval of spreading should be designed carefully by taking in consideration the number of contending vehicles because a large interval with few contenders will increase the transmission delay beacon expiration problem. On the other hand, a small interval with high number of contenders leads to increasing the probability of collisions.

The table 4.1 shows that two mechanism CW adaptation and the packet rate adaptation received a lot of attention from the VANET research community. On the other hand, the data rate adjustment, the physical carrier sense adaptation and the transmission power adjustment are only rarely considered, despite the significant improvement they could bring. They have low efficiency and they could even have the opposite effect and lowering the performance of safety applications under high node density. Whereas, the Transmission timing control is a promising technique for CSMA-based MAC mechanisms to decrease the collision probability and increase the packet reception rate. It is the principle argument of the proposal of this thesis. Note that the adaptation of these transmission parameters are generally achieved based on the Local Density estimation and CBR.

On the other hand, the category of schedule-based protocols is exclusively represented by the TDMA-like MACs. Before the definition of the WAVE standard, this category MACs paid a cultural penalty few decentralized TDMA-like protocols had been studied for wireless and most of them required a central coordinator and this would not be applicable for VANETs. Moreover, synchronization had not been extensively studied and it is still commonly believed that a synchronous and connection-oriented approach will be affected by mobility and the increasing

number of nodes lead to a blocking performance: as soon as it exceeds the number of available slots, some nodes will not be allowed to transmit.

Over the years, the TDMA-like MACs have been demonstrated to be applicable in the context of VANETs. To mention the most significant features, some of them can reuse the same physical layer as CSMA/CA and adopt decentralized mechanisms and they can work at vehicular speed. Additionally, they have the ability to be flexible and to have a strong potential to solve the main issues of CSMA/CA (scalability to hidden terminals) thanks to a clever spatial multiplexing—especially if coordination is performed over more than one hop. When talking about TDMA-like MACs for VANETs, in most cases it inherently refers to a connection-oriented protocol. The reason is that CSMA/CA already represents an improvement over the connectionless slotted Aloha [142] in which packets are sent immediately and, in the event of a missing acknowledgment, a retransmission is made after a random backoff. Thus, synchronization is worth only when it permits to spread transmissions over space, with an ordered approach—by assigning slots. The efficiency of S-Aloha is higher than pure Aloha, but it still lacks the concept of slot reservation. It was first introduced with the Reservation S-Aloha (R-Aloha) protocol [143], in which nodes continuously listen to the channel to identify free slots and, when one needs to transmit, it will just pick a free slot and keep using it as long as it needs it.

Sensing-based coordination is one of the mechanisms used by Some TDMA-like protocol to reserve slots. It consists to listen to the channel first frame and select a free slot before to start sending packets. This kind of reservation is just based on sensing/receiving (not on signaling). However, using the sensing-based slot reservation alone is considered today too challenging and critical in a very dynamic environment and with rapidly variable topologies such as VANET.

Position-based signaling is a slot reservation mechanism in which TDMA slots are allocated based on a vehicle's instantaneous geographical location. It can be local without sharing a slot-location mapping between vehicles. They only need to broadcast their locations between each other over one hop or two hops to ensure a better use of slots without hidden collisions. Otherwise, in the Global slot/space Map strategy the rationale is to divide the roads into segments each one corresponds to a slot of a TDMA frame structure. This mechanism is pre-allocated a TDMA slot which uses the SDMA approach. The major advantage of such mechanism is that there are no message collisions between vehicles in the same two-hop neighborhood, without

any exchange of slots' allocation information it keeps the protocol overhead very limited. Also, this mechanism offers bounded delay, and there is no reconfiguration latency due to network topology changes. However, although the hidden terminal problem can be eliminated, there are some drawbacks that need to be considered. The first one is the depending on the absolute position whose precision in urban areas, also with GNSS (GPS), is quite likely to exceed the width of a segment (5 m in [21]). As a result, both due to limited precision in their positioning or to a high density of cars, more nodes might use the same slot, leading to a poor reception or collisions. Additionally, the system requires complete pre-mapping of geographical locations to TDMA slots, which may have practical limitations especially when the huge geographic coverage of a transportation system is considered. Also, dimensioning optimal segment size for varying application requirements and vehicle density is a non-trivial problem. This method is easy to implement in highway scenes but under the city scenarios it is difficult to divide roads into segments when the topology of the roads is complex. Moreover, this approach does not maximize the use of available bandwidth. At any point in time, a large portion of the roadway is likely to be unoccupied, and time slots associated with this part of the roadway will go unused. Slot State signaling for distributed TDMA slot allocation can be achieved by two ways out-of-band and In-band. The first, which is out of-band signaling, consists that vehicles send control packets during scheduled data slots to disseminate slots' allocation information. Based on its slots' allocation information, a vehicle is able to select a collision-free transmission slot, which is used for subsequent data as well as control packet transmissions. However, this protocol may suffer from high slot reallocation latency after a network topology change. Moreover, an explicit signaling over multiple hops would serve as a countermeasure. On the other hand, In-band signaling consist of adding the slots' allocation information to the header of the packets so vehicles can detect the available slots by listening to this header which is particularly suitable for vehicular. However, this mechanism has a critical problem that causes large overhead by containing ID Fields (IDF) as many as the number of time slots per frame when the MAC address is used as IDF of each vehicle. Therefore, the header becomes relatively large, compared to the payload size and the header will be increased as the density increases. The slot status signaling is an effective mechanism for distributed TDMA slot allocation but it should not represent an excessive burden and should work effectively also under mobility. The basic theories of these TDMA protocols are similar which operate based on periodically broadcast messages. Control informa-

tion used to coordinate the usage of time slots needs to be packed in the periodically broadcast messages (In-Band mode) or send as control messages (Out-of-Band mode). According to which vehicles know the slot usage information and detect whether transmission collisions might occur. Each vehicle selects one time slot for itself and during this time slot, it sends packet. Vehicles are not aware of the acquired time slots unless they wait for a frame length and then make the judgment based on the messages received. The access to the select slot is direct in which the vehicle sends their packets immediately in its slot without any sensing of the channel.

In mobile wireless communications like VANET, when using TDMA, there are two additional problems, named ‘access collision’ and ‘merging collision’ which occurs. The access collision occurs when several vehicles transmit a packet simultaneously in the same time slot, the senders do not detect the signals of each other, and the packets collide on the neighbor’s side. The senders are not aware of whether the packets they transmitted collided or not, if there is no feedback for the transmitted packet. On the other hand, the merging collision is a problem that can occur when vehicles are in high mobility and the network topology change frequently. Thus, when several vehicle using the same time slot that are outside the transmission range of each other become in their communication ranges due to their mobility, it may cause packet collisions to occur in these shared ranges.

A promising solution for these two problems is the hybrid MAC or the contention access which combines CSMA/CA and TDMA. In which, the vehicle senses the carrier signal before transmitting packets in the front part of the time slot. The use of CW minimizes the probability of collisions between the neighbor and the merging contenders of a given slot. Moreover, it will give a priority to the slot owner, who succeeded in transmitting a packet in the same time slot of the previous frame over the other competitors which are not informed about the status of the that slot. Recently the researchers consider this combination to avoid access and merging collisions

Another challenge of TDMA is in the bandwidth management after the time slots assignment for a given vehicles. If some of them have no data ready to transmit or if they leave their neighbors then their time slot are wasted for a given period of time. Likewise, if the vehicle has a large amount of data, it can only transmit the fraction that occupies the size of the time slot. The rest of the packet is buffered for later transmission. On the other hand, with the CSMA/CA-based protocol the vehicle accesses the channel only when needed and it can

broadcast packets with different frequencies and different packet sizes. These advantages have to be introduced into TDMA mechanism to eliminate the challenges mentioned above.

4.6 Conclusion

Improving road safety in VANETs requires efficient and reliable MAC protocols. Thus, this chapter presents an extensive overview of MAC protocols for Vehicular Networks which exist in the literature. These protocols make use of various channel access schemes to transmit ITS safety messages. They are categorized in two main classes: contention-based methods represented by CSMA-like protocols and contention-free methods represented by TDMA-like protocols. Both of them have benefits and drawbacks which all must be considered carefully when developing traffic safety applications.

As a general observation, The CSMA-like protocols are suitable for event-driven packet, because of its simpler operating and its ability to support variable packet sizes and it does not need synchronization among the vehicles. However, the problem arrives when several vehicle decide to transmit simultaneously, only a fraction of the time is devoted to successful transmissions, while the rest is wasted because of the direct collisions as well as the hidden collision. The risk increases with the increase of vehicle density and the problem becomes critical with the time-triggered packets such as beaconing when all vehicles start transmission at the same time periodically. Therefore, the promising collision resolution mechanism must be used and combined with backoff mechanism adaptation such as beacons rate adaptation and transmission timing adaptation.

On the other hand, TDMA-like protocol is suitable for periodic transmission because of its ability to avoid collisions between vehicles in the same two-hop neighborhood. The packet size is fixed and should fit into one slot which is the case with this kind of transmission. additionally, it is predictable in the sense that a vehicle always will get channel access within a bounded time upon request which is a critical requirement for ITS safety applications that require fast reconfiguration and low message delivery latency. However, the primary researchable question that still remains: how to cope with frequent topology changes by fast TDMA reconfiguration with light overhead required for self-organization. These difficulties with TDMA suggest that a stand-alone TDMA scheme is not practical. Even if we have an efficient TDMA schedule,

the other factors such as interference irregularity, time-varying channel conditions and clock synchronization errors would diminish the benefitts of TDMA.

As a conclusion, combining the advantages of both mechanisms, The CSMA-like protocols and TDMA-like protocol, has been a long research goal to propose an efficient MAC protocol.

CSSA MAC: Carrier Sense for Slotted-ALOHA random multiple access MAC

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5.1 Introduction

The large review of the related work presented in the previews chapter allows underlining the advantage and the limitations of the existing MAC protocol for beaconing communications. Moreover, it helps in showing the novelty of the proposed MAC approach in this thesis. This chapter presents the system analysis of a novel MAC protocol called Carrier Sense for Slotted-ALOHA random multiple access MAC (CSSA MAC). It is developed specifically for VANET to support one-hop and beaconing safety communications on the CCH efficiently. CSSA MAC tackles the start-of-interval contention problem caused by the IEEE 1609.4 channel switching

from SCH to CCH. It aims to reduce transmission collisions by combining some MAC mechanisms and keeping simplicity without any overhead. Finding the optimal SW size according to the Local Density (LD) which is the number of contender vehicles in two hops was the main objective of the analytic work. In particular, it tries to estimate the best trade-off between the level of beacons transmission contention and the time gaps where the contention ratio (CR) allows reflecting the probability of collision and successful transmission. The analytic study is based only on counting the number of occupied and empty STTs as a factor of contention without any real transmission which does not allow calculating the exact probability of transmission collision and time gaps ratio. Therefore, this chapter presents also a simulation study through a network simulator to confirm the analytic finding and to evaluate the performance of CSSA MAC as compared with some famous MAC protocols.

The chapter is organized as follows. The Section 5.2 presents an analytic study for the motivation problem of the current research which is the transmission collision problem caused by switching mechanism of the IEEE 802.11p/1609.4 standard. The Section 5.3 gives an overview of CSSA MAC basics and the Section 5.4 shows a mathematical analysis study to evaluate the functionality of the CSSA MAC protocol and justify the parameters used in the simulation part. For the simulation study, the Section 5.5 presents the contender MAC protocols to be compared with the CSSA MAC. The Section 5.6 gives an overview of the simulation parameters and the performance metrics used for the MAC protocols evaluation which reflect the requirements from C-ITS for safety applications and also presents the Simulation Results. Finally a conclusion is presented in Section 5.7.

5.2 Mathematical Analysis of collision problem under IEEE 802.11p/1609.4

The important part in IEEE 1609.4/802.11p standard is the channel switching scheme between SCH and CCH intervals. However, the most potential problem associated with that is the “start-of-interval contention” problem that without special care there could be a large amount of traffic waiting to be transmitted at the start of each CCH Interval, as shown in Figure 5.1. The channel access procedures of the IEEE 802.11p MAC protocol could result in an artificially high level of packet collisions.

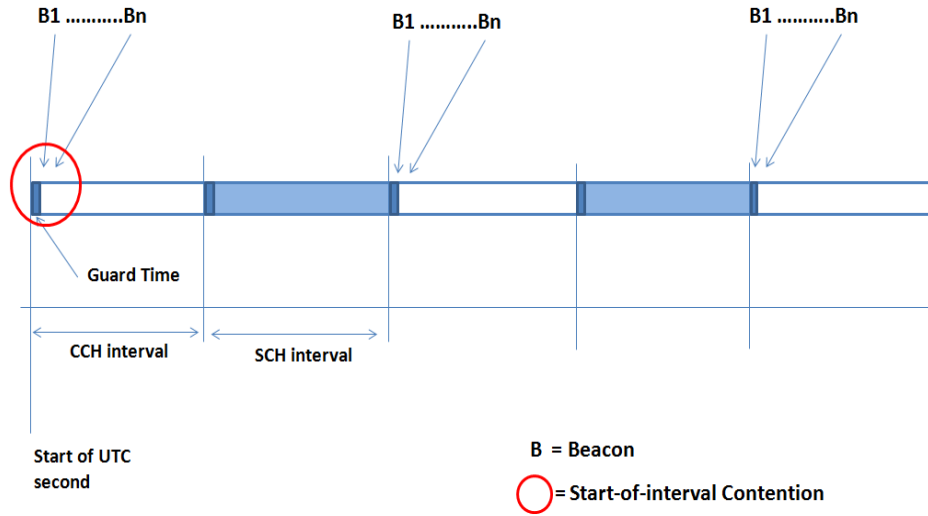


Figure 5.1: The start-of-interval contention problem under the IEEE 1609.4 switching mechanism.

The standard solution of WAVE standard against the start-of-interval contention problem requires the medium to be declared busy during the guard interval between the CCH interval and the SCH interval. It forces the involved vehicles to perform the 802.11p collision avoidance at the beginning of each CCH interval. However, for the IEEE 802.11p, the contention window (CW) sizes to be used in the collision avoidance are only 3, 7, or 15, depending on the access class (AC) [143]. Since the binary exponential backoff of the window does not apply to broadcast, the collision probability for beacons can become large if the number of vehicles grows in the communication range. The objective of this section is to investigate the start-of-interval contention problem through an analytic study where the successful transmission probability can be calculated as follows.

At the beginning of CCH, (k) contending vehicles compete to transmit at the same time. A successful transmission is considered if only one of them sends its beacon exclusively, which means that the backoff of the winner has to be unique compared to the other contenders and expires before them otherwise collision will be happened.

The equation (5.1), which defined as $p(k, cw, d, v)$ and visualized in figure 5.2 [88], represents the probability that (k) vehicles generate beacon messages at the same time and select the back-off counter from the contention window of (w) slots, and $(d - 1)$ have passed from the counting down before the first transmission attempt, and $(v \leq k)$ vehicles transmit in the (d) back-off

number.

$$p(k, cw, d, v) = \left(1 - \frac{d-1}{w}\right)^k \binom{k}{v} \left(\frac{1}{w-d+1}\right)^v \left(1 - \frac{1}{w-d+1}\right)^{k-v} \quad (5.1)$$

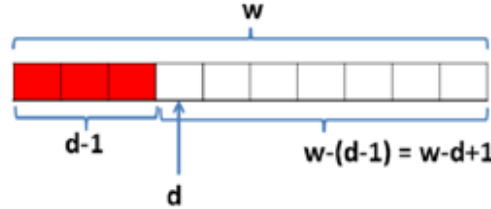


Figure 5.2: Visualization of the equation 5.1

Where :

- $\left(\frac{1}{w}\right)$ is the probability that a vehicle selects one of the backoff numbers (d) from (w),
- $\left(1 - \frac{d-1}{w}\right)$ is the probability to not select a back-off number lower than (d) which represent the interval $[0, d-1]$
- $\left(1 - \frac{1}{w-d+1}\right)$ is the probability to not select the slot (d) from (w-d+1)
- $\binom{k}{v}$ represents all the possibilities where (v) from (k) vehicles can select (d),

The probability of the successful transmission is when one and only one vehicle ($v=1$) can select the back-off number (d).

Let $T(k, w)$ be the random variation which counts the number of transmissions at the beginning of CCH among (k) contenders and in every backoff number value. Therefore, the $P(T(k, w)=1)$ presented in the equation (5.2) is the probability of a successful transmission:

$$P(T(k, w) = 1) = \sum_{d=1}^w P(k, w, d, 1) \quad (5.2)$$

Figure 5.3 presents the probability of successful transmission at the beginning of the CCH under different channel loads and contention windows. The channel load that a vehicle perceives depends on the number of vehicles in range and their individual message generation rates. All the vehicles are in communication range each other and the message rate is one beacon per CCH

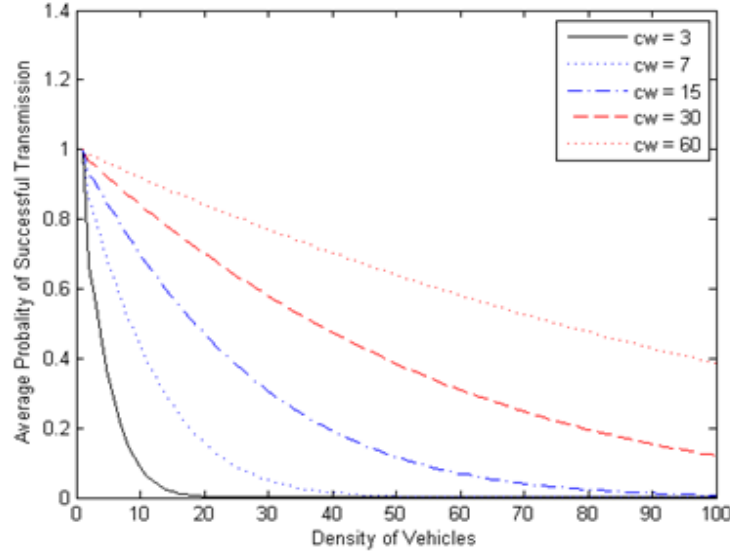


Figure 5.3: Probability of the first successful transmission at the beginning of CCH, with a different vehicle densities and contention window sizes.

interval which result in offered load equal to the density of vehicle. The graphs of Figure 5.3 show that an increasing channel load leads to decreasing of the successful transmission no matter the contention window size. With the contention window values used in the IEEE 802.11p standard for safety communication which are $cw=3$ and $cw=7$, the successful transmission will be 0% over the offered load 20 and 40 respectively.

The analysis results shows that the performance of the periodic broadcast is strongly influenced by the choice of the CW size in the normal or dense vehicular environments. Therefore, it is important to reinforce the CW adaptation by another efficient DCC mechanism for a better broadcast performance which adapt the change of the vehicle density in order to reduce the channel load and avoid channel congestion.

5.3 The CSSA MAC protocol

5.3.1 The main idea

The collisions of periodic safety message broadcasts for the IEEE WAVE system are left to the IEEE 802.11p medium access control (MAC) to resolve with small contention window sizes used in the 802.11p amendment. However, the MAC offers only limited solution to the collision problem, particularly toward the beginning of the CCH interval. Recently various proposal in

the literature, investigate the idea of spreading out the channel access of the transmitters during the CCH interval to enhance the switching mechanisms [99],[106],[108], [104], with different synchronous or asynchronous rendezvous mechanism, in order to avoid the contention problem. These mechanisms propose slight modifications to the IEEE 1609.4 standard to improve it and to the MAC procedures able to mitigate the influence of the switching mechanism. However, these proposals do not investigate the optimal spreading of channel access according the channel load which avoid the unnecessary time gabs between the successful transmission under a sparse network and a contention in case of dense network.

This section proposes a novel scalable random access MAC for vehicular networks with the objective to prevent the start-of-interval contention problem which occur upon switching to the CCH. It aims to provide an efficient one-hop broadcast access on the CCH, and attempts to minimize the risk of direct and hidden collision problems.

The proposal is called **CSSA MAC** (Carrier Sense for Slotted-ALOHA random multiple access MAC) which tries to combine the advantageous and the simplicity of the two MAC mechanisms: CSMA and Slotted-ALOHA. It can be seamlessly integrated in IEEE 1609.4 on top of the IEEE 802.11p standard.

Its main idea is to spread the transmission time of beacons of the contending vehicles over a Spreading Window (SW) from the CCH interval. Therefore, CCH period is virtually slotted the same way as S-ALOHA MAC method where the virtual slots represent the possible Start of Transmission Times (STT) of the beacons.

The beacon spreading process is the fact of randomly assigning a STT from the SW to each beacon. Hence, with this mechanism CSSA MAC aims to ensure a more efficient use of the limited bandwidth available. Therefore, an analytical analysis is made in order to calculate the optimal SW size according to the number of contending vehicles. Using a mathematical model, it is possible to predict the ratio of contention, the probability of successful transmission and collisions, and the wasted time between the first and the last successful transmission.

CSSA MAC protocol consists of two parts: (1) spreading the vehicle's beacons: at the beginning of each CCH interval, the beacons are spread in time over the SW (a STT is randomly allocated for each beacon). Such solution can be enabled through a minor modification to the IEEE 1609.4 standard; and (2) medium access: when the STT is reached, a vehicle has a chance to access the channel, and attempts to transmit using the conventional IEEE 802.11p's

CSMA/CA.

5.3.2 System model

The system is formed by vehicles which can transmit, receive and forward beacon messages to/from vehicles within its one-hop of each other. The communication links are assumed to be symmetric, and each vehicle in the network has a same communications range, which is fixed to a specified value. The carrier sensing range is assumed to be the same as the communications range. The system uses the MAC protocol as defined in IEEE 802.11p/1609.4, and operates in one CCH which is used for the transmission of a beacon message, also known in the WAVE architecture as a (BSM) and (CAM) in ETSI architecture. These messages are always transmitted at the beginning of each CCH interval. All the vehicles transmit beacon packets of a same size, and at a same transmission rate λ , and they start at the same time instant. It is assumed that the transmission duration between two successive beacons is equal to the CCH interval which is reasonable to limit the lifetime of a beacon message to one CCH interval. The time synchronization at the MAC layer is also required by our scheme, and it can be achieved in real deployments by relying on the Coordinated Universal Time (UTC), which can be obtained easily using GPS time stamps.

The CCH interval is partitioned to a variable number of virtual STT where their borders and size are calculated at the beginning of each CCH interval according to the beacon size and the beacon transmission rate. Not like the TDMA method which uses a constant number of time slots with a fixed size. Note that the $STT_{CCH} = \{i/0 \leq i \leq N\}$, represents the set of STT of the CCH interval and SW set is part of it ($|SW| \leq |STT_{CCH}|$), as shown in Figure 5.4.

For that the protocol defines the Total Transmission Duration (TTD) of the beacons which consists of a guard time (T_{Guard}) which guard interval that accounts for the propagation delay and timing inaccuracy and an AIFS period and the minimum Contention Window (CW_{min}) interval and the beacon transmission time (T_{Beacon}). Note that the CW_{min} is used to ensure the competition between the vehicles having selected the same STT, when they arrive to the MAC layer. However, with S-ALOHA, the TTD consists of only (T_{Guard}) and T_{Beacon}. (see Figure 5.5). The duration of the TTD value, used by CSSA MAC, can be adjusted according to

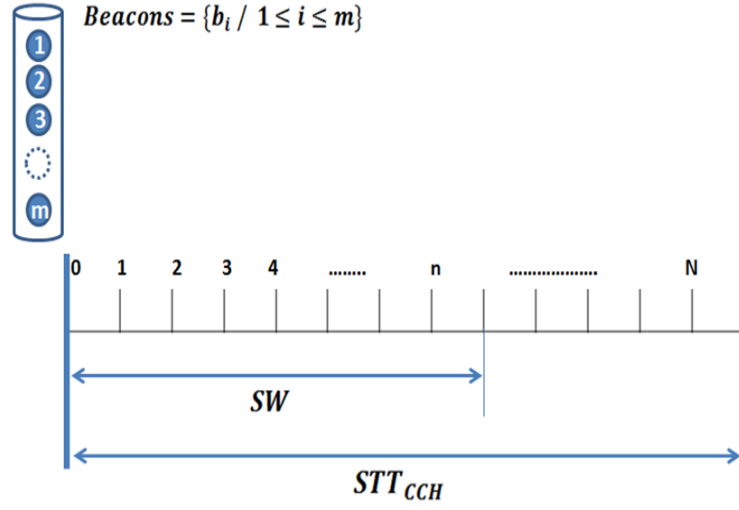


Figure 5.4: The virtual time slicing and SW size compared to the CCH interval.

the CW value and the chosen beacon size as follows:

$$TTD = T_{Guard} + T_{AIFS} + T_{CW} + T_{Beacon}$$

After that the channel is slotted virtually and the size of STT_{CCH} is calculated as follows:

$$|STT_{CCH}| = \left\lceil \left(\frac{1}{\gamma} \right) div TTD \right\rceil$$

Where γ refers to the beacon transmission rate (note that $\left(\frac{1}{\gamma} \right)$ is equal to the CCH interval).

$\forall b \in Beacons, \exists STT \in STT_{CCH} :$

$STT = Random(0, SW)$ and $WaitingTime(b) = STT \times TTD$.

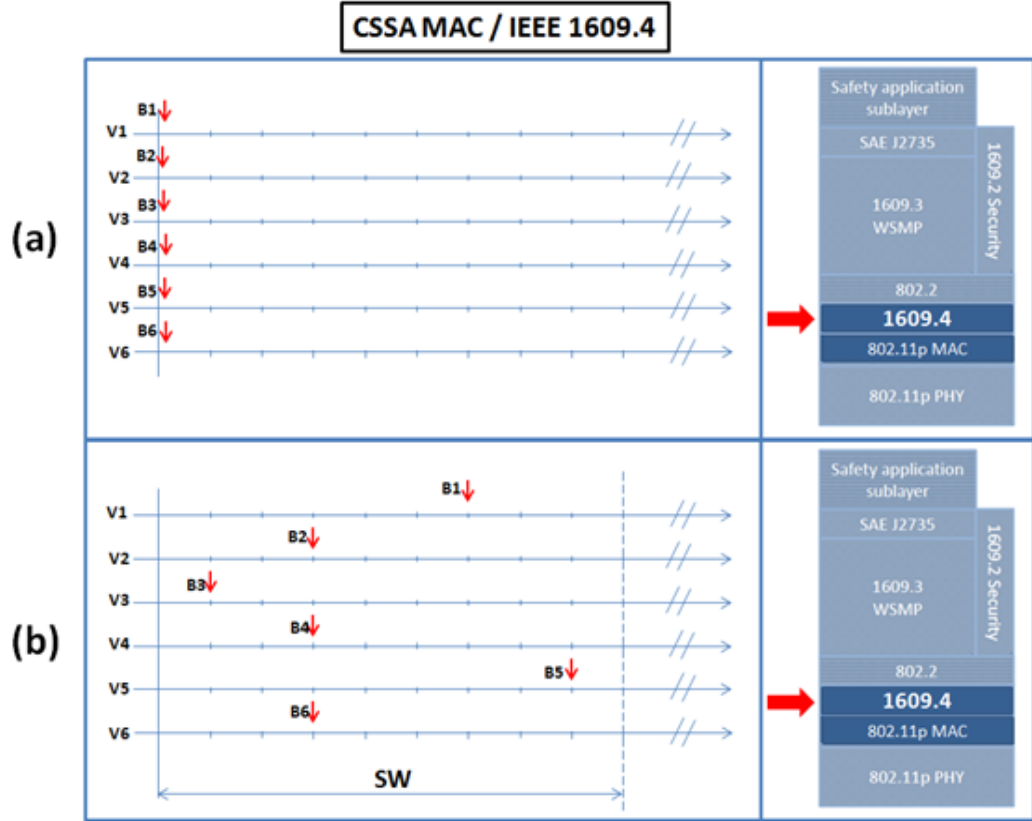


Figure 5.6: CSSA MAC functioning: (a) beacons simultaneously arriving to the IEEE 1609.4 layer; (b) beacons being spread over the SW.

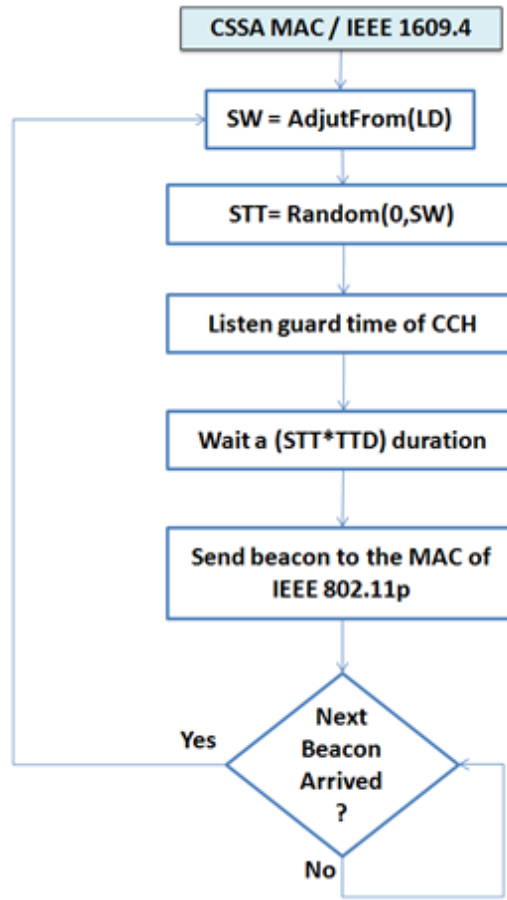


Figure 5.7: The CSSA MAC method for beaconing: the IEEE 1609.4 procedure.

5.3.4 Medium access using IEEE 802.11p's CSMA/CA

When it is time for a vehicle to access the channel and attempt to transmit, the beacon is passed to the MAC layer (i.e. IEEE 802.11p). It may happen that several beacons fall within the same VSTT, meaning that they will compete for channel access. Before transmitting the beacon packet, each vehicle invokes the back-off procedure using the minimum contention window interval (CW_{min}) to reduce the collision probability between them. The back-off counter is decremented only if the channel has been idle for one physical slot (∂); otherwise, the counter is frozen until the end of the current transmission. When the counter reaches zero, the vehicle broadcasts its beacon (see Figure 9). If there are no contenders for the selected STT, the vehicle sends successfully without any contention; otherwise, it will face a risk of collision (see Figure 5.9).

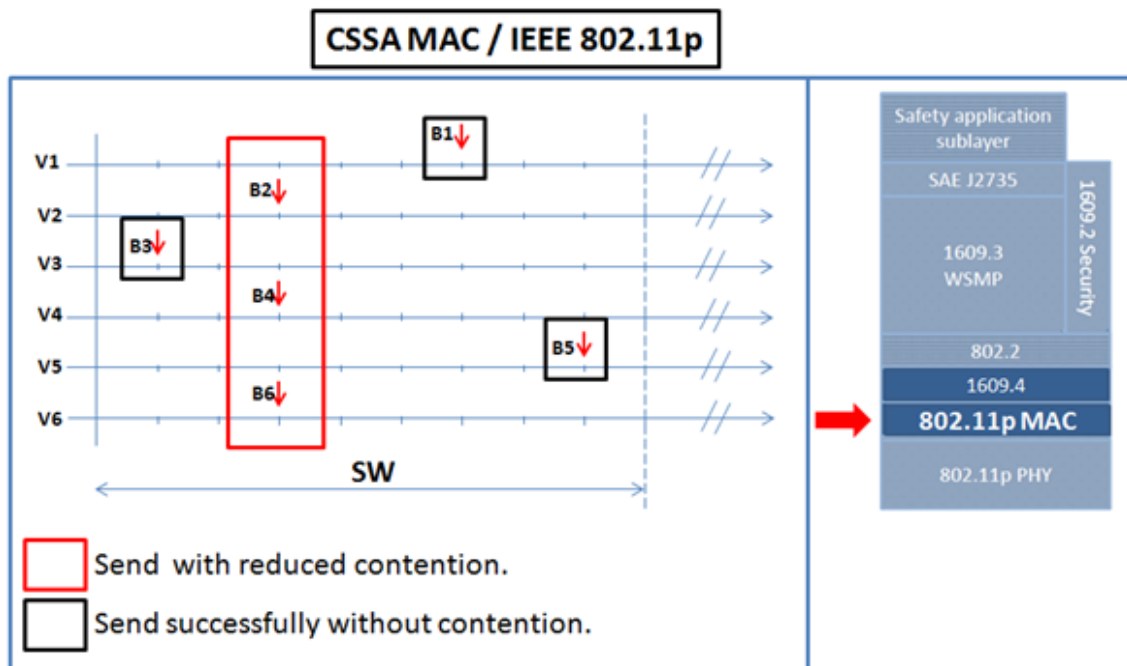


Figure 5.8: The CSSA MAC method for beaconing: the IEEE 1609.4 procedure.

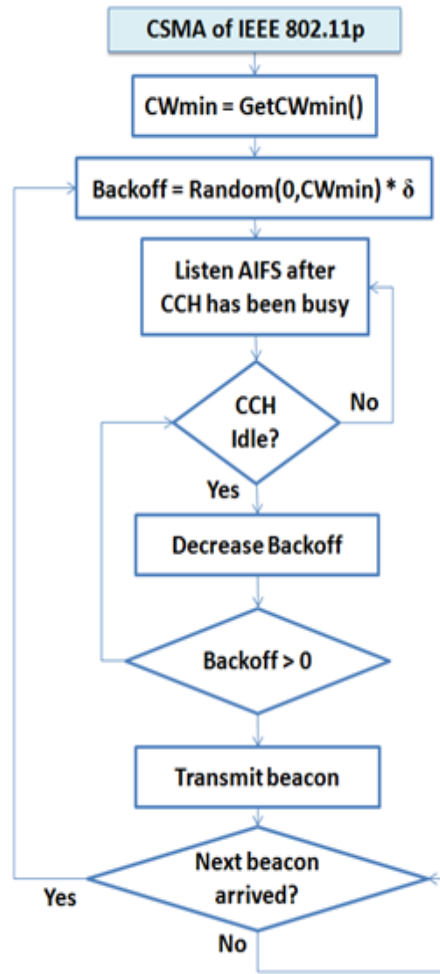


Figure 5.9: The CSSA MAC method for beaconing: the CSMA/CA procedure of IEEE 802.11p.

5.4 Mathematical Analysis of the optimal size of SW

Spreading the beacons of vehicles over the SW results in both an occupied STTs (STTs means a set of STT) and time gaps. An STT is considered occupied if at least one beacon is assigned to it. The time gaps represent the empty STTs between consecutive occupied STTs. The spreading system considers two cases: (1) if the number of beacons is relatively high compared to the size of the SW, each STT can be assigned to several beacons, which increases the level of contention, as shown in Figure 5.10 (a); (2) if the size of the SW is relatively large compared to the number of beacons, there will be a lot of time gaps between the occupied STTs (see Figure 5.10(b)).

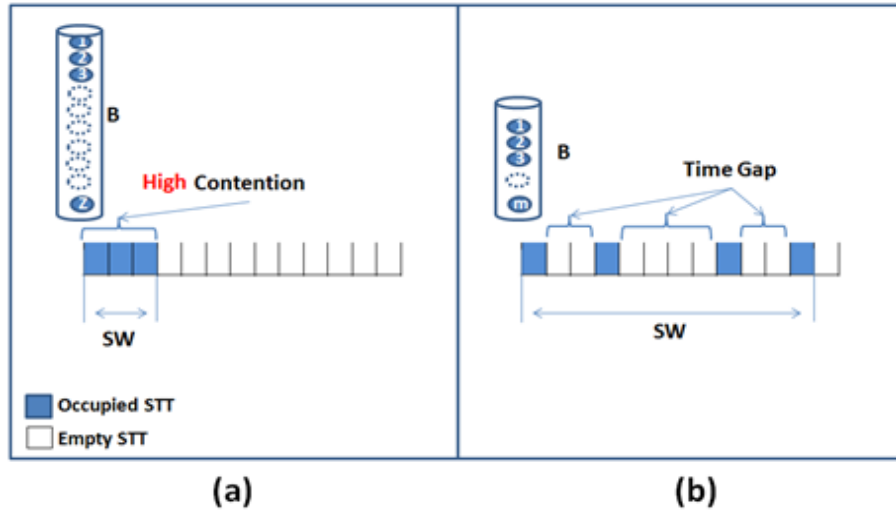


Figure 5.10: Spreading cases: (a) when the number of beacons is higher than the size of the SW; (b) when the size of the SW is larger than the number of beacons.

The objective of this work is to calculate the optimal size of the SW according to the number of beacons, so that it is able to provide the best trade-off between the chances of collision and the ratio of time gaps. To meet this goal, it must satisfy the safety requirements for the target application, which are: high reliability, predictable delay, and scalability. For that purpose, the first step to be investigated is the prediction of the number of occupied STTs. This is equivalent to the famous Occupancy problem [144], where (m) distinguishable balls are randomly distributed into (n) distinguishable boxes.

To begin with, let $O(m,n)$ be the random variable which determines the number of the occupied boxes when distributing (m) distinguishable balls into (n) distinguishable boxes, and $P(O(m,n)=k)$ be the probability that (k) boxes are occupied. The probability is calculated as follows:

$$P(O_{m,n} = k) = \frac{U(m, n, k)}{N(m, n)} \quad (5.3)$$

Where $U(m, n, k)$ gives the number of possible ways to distribute (m) balls in (k) boxes, where (k) boxes are occupied, and $N(m, n)$ represents all possible cases of distributing (m) balls over (n) boxes. $U(m, n, k)$ is defined as follows:

$$U(m, n, k) = A_k^n S(m, k) \quad (5.4)$$

$$S(m, k) = \frac{1}{k!} \sum_{j=0}^k (-1)^j (k-j)^m$$

Where $S(m, k)$ is named “the stirling number of the second kind”. This way, the deduced expression of equation (5.4) can be written as

$$U(m, n, k) = \binom{n}{k} \sum_{j=0}^k (-1)^j (k-j)^m \quad (5.5)$$

The number of all possibilities by which (m) distinguishable balls can be distributed into (n) distinguishable boxes is:

$$N(m, n) = n^m \quad (5.6)$$

Equation (5.3) can be deduced from equations (5.5) and (5.6), and can be written as follows:

$$P(O_{m,n} = k) = \frac{\binom{n}{k} \sum_{j=0}^k (-1)^j (k-j)^m}{n^m} \quad (5.7)$$

The equation is implemented and compared with a simulation performed in Matlab, where we distribute N beacons over a SW number of STTs. Note that, in all simulations, the size of the SW is taken as being arbitrarily equal to the number of beacons (NB=SW).

The graphs presented in Figure 5.11 show a matching between the analytic and the simulation results, thus confirming the correctness of the equation used. They show the occupancy probability for different number of beacons. It is noticeable that the occupancy possibilities do not have the same probability of appearance. In each experience, there is one occupancy possibility which has the highest probability; we called it the Highest Occupancy Possibility (HOP). It represents the number of occupied STT which have the highest chances to appear when the beacons are spread over the SW.

The graphs of Figure 5.12 present the impact of the SW size on the occupancy possibilities and on the HOP, for different values of the NB (number of beacons) parameter. It is shown that, when the SW increases, the whole graph shifts to the right, and the value of the HOP gets closer to the maximum number of beacons. This means that the occupied STTs will be receiving only one beacon (on average) as the SW gets bigger.

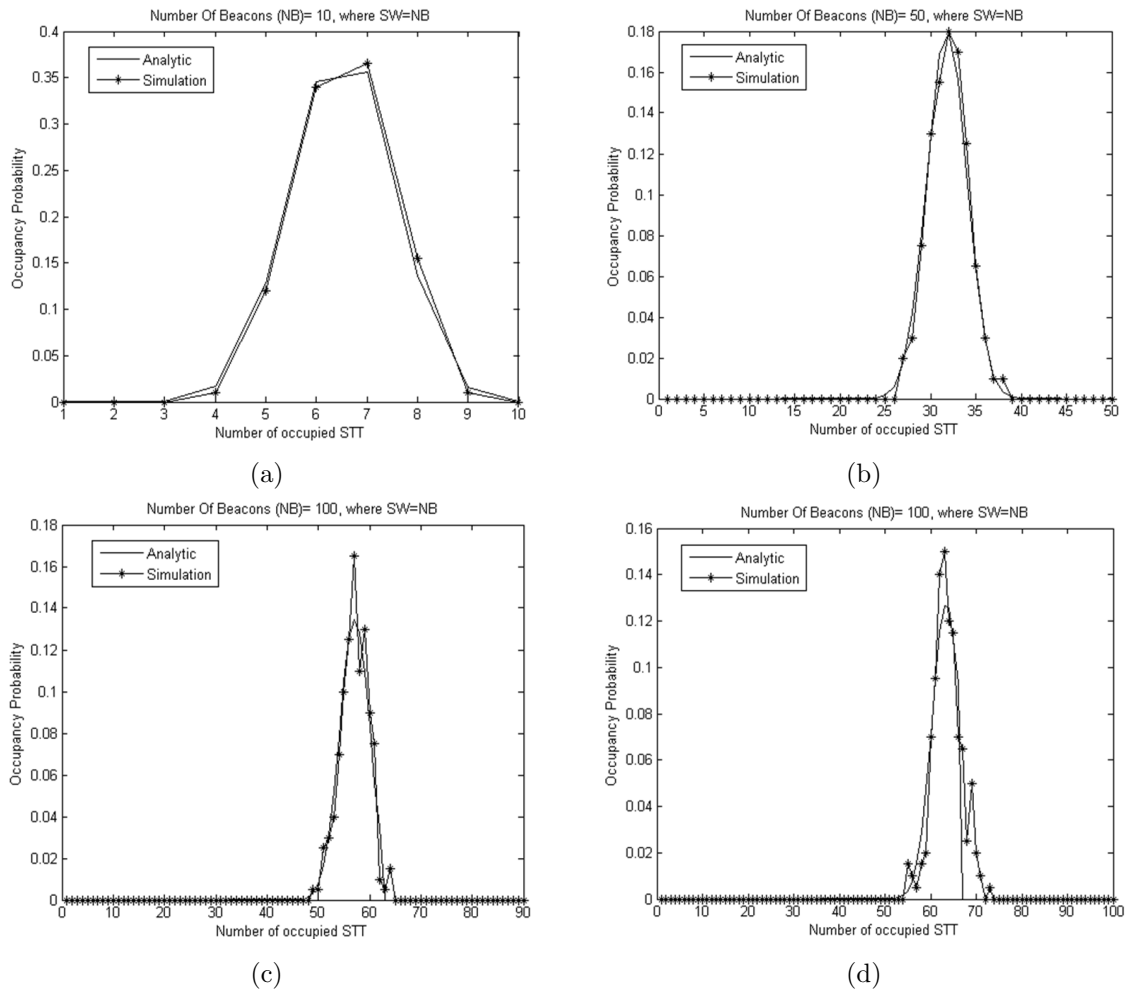


Figure 5.11: Nombre de message reçus dans un environnement multi-trajets

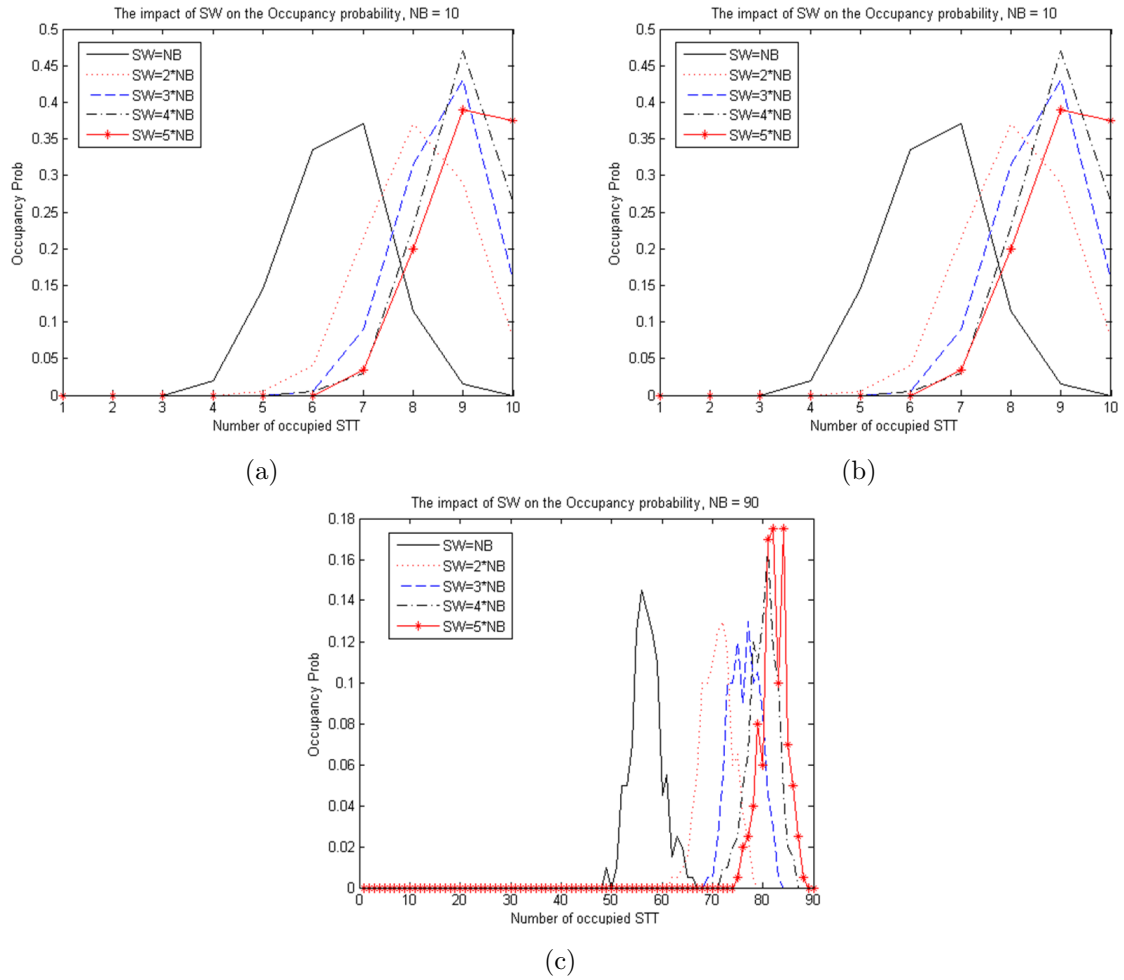


Figure 5.12: Nombre de message reçus dans un environnement multi-trajets

A more general study about the impact of the SW on the HOP is needed to ascertain the previous results. Let $HOP(NB, SW)$ be the function which returns the HOP value when spreading NB beacons over SW. This way, the Occupancy Ratio (OR) can be defined as follows:

$$OR(NB, SW) = \frac{HOP(NB, SW)}{NB}$$

$$\lim_{HOP \rightarrow 1} OR \approx 0, \quad \lim_{HOP \rightarrow NB} OR = 1$$

The worst case takes place when the HOP is equal to 1, meaning that the occupancy is minimal, and the best case occurs when the HOP is equal to the number of beacons (NB); in this case, each Occupied STT receives only one beacon. Now, let us define the Average Occupancy Ratio (AvgOR) for a set of NB values, and for a given SW. The AvgOR can be determined as follows:

$$\forall SW \in SWSet, \forall NB \in NBSet :$$

$$AvgOR(SW) = \frac{\sum_{NB} HOP(NB, SW)}{|NBSet|}$$

Figure 5.13 shows the analytic and the simulation results of AvgOR, where the average results of different number of beacons are $taken \sim NBSet = \{10, 20, \dots, 100\}$ for each SW size. The SW sizes taken represent a set of multiples of NB, where $SWSet = \{k * NB / k = 0, 0.5, 1, 1.5, 2, 2.5, 3\}$. Note that, when multiple NB values equal zero ($k = 0$), it means that SW has just one STT ($SW=1$). It is remarkable that the results of both analytic and simulation graphs clearly match each other; in addition, when the SW increases, the AvgOR increases too. This means that the occupancy ratio increases when the SW size increases.

The results of the AvgOR graph can be used as a model to estimate and predict the HOP for any number of beacons belonging to the NBSet, and for any SW size belonging to the SW Set. The HOP can be calculated using the following formula:

$$\forall SW \in SWSet, \forall NB \in NBSet :$$

$$HOP(NB, SW) = Round[AvgOR(SW) \times NB]$$

The level of contention has an inverse relation with the HOP: the more the HOP value comes

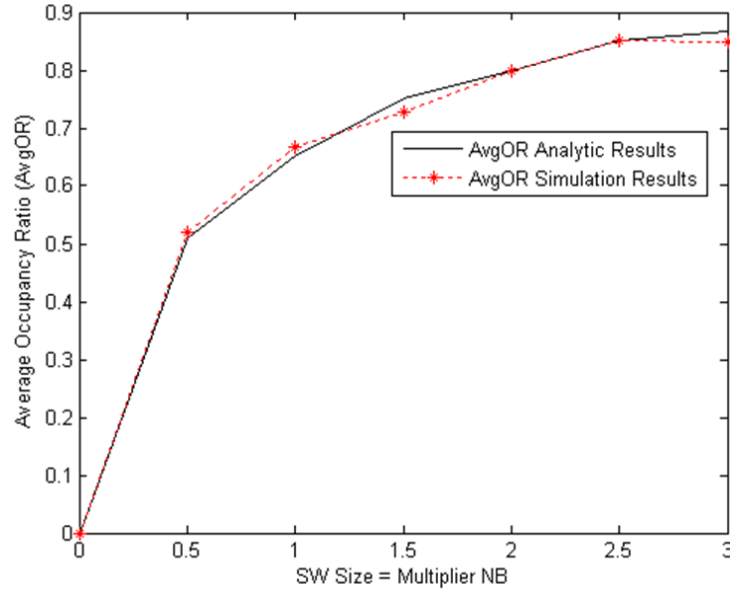


Figure 5.13: Analytic and Simulation results for the AvgOR parameter.

closer to NB, the lower the probability of contention will be, and vice versa. So, let us define the Average Contention Ratio (AvgCR) for a different number of beacons, and different SW sizes. The AvgCR is determined as follows:

$$\forall SW \in SWSet, \forall NB \in NBSet :$$

$$AvgCR(SW) = 1 - \frac{\sum_{NB} HOP(NB, SW)}{|NBSet|}$$

The Figure 5.14 shows the analytic and simulation results of AvgCR. Note that, the simulation is performed using MATHLAB and it is just for calculating the occupied and the empty STTs without transmission simulation. The graph shows that the risk of contention decreases when the SW size increases.

The second step to be investigated is the prediction of the time gaps, which can also be extracted from the occupancy problem. Note that the time gap is the sum of the Empty STTs between the beginning of the CCH and the last occupied STT. Predicting the Time Gap (TG) depends on two things: (1) the $HOP(NB, SW)$; (2) and the Position of the Last Occupied STT, $PLOSTT(NB, SW)$, after spreading the N beacons over a SW of STTs. It can be given by the following formula:

$$TG(NB, SW) = PLOSTT(NB, SW) - HOP(NB, SW) \quad (5.8)$$

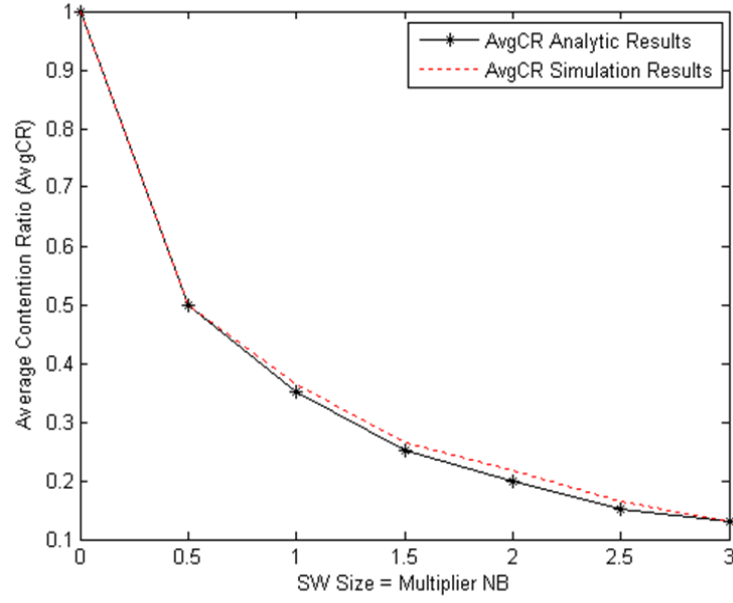


Figure 5.14: Analytic and Simulation results of AvgCR.

Figure 5.15 shows the different cases of PLOSTT(NB,SW). Notice that this value can be between HOP(NB,SW) and SW, which represents the minimum and the maximum value of PLOSTT(NB,SW), respectively. In order to predict the TG it is necessary to know which PLOSTT(NB,SW) case has the highest probability of happening.

Let C_K^M , where $M = HOP(NB, SW)$ and $k = [M, SW]$, represent all combinations of occupying the M start transmission times (STTs) from k. It may happen that the STT number k is not taken in some combinations. So, let us define CL_K^M , which takes only the combinations where the last STT (number k) is used, that is, it represents Case(k), and it can be calculated as follows:

$$Case(k) = CL_K^M = C_K^M - C_{K-1}^M \quad (5.9)$$

By applying the following relation: $C_n^p = C_{n-1}^{p-1} + C_{n-1}^p$, the equation (5.9) can be rewritten as follows:

$$CL_K^M = [C_{K-1}^{M-1} + C_{K-1}^M] - C_{K-1}^M = C_{K-1}^{M-1}$$

$$Case(k) = CL_K^M = C_{K-1}^{M-1} \quad (5.10)$$

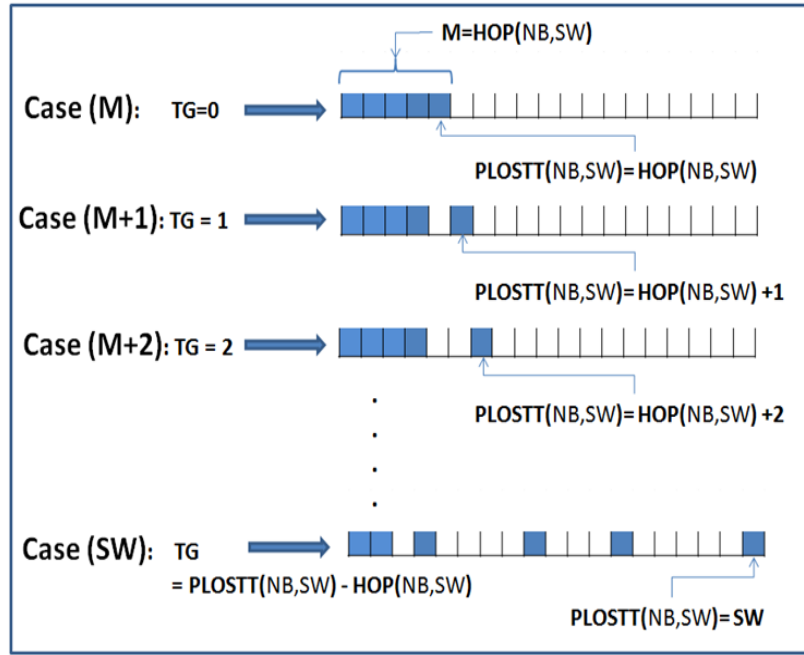


Figure 5.15: Different cases of PLOSTT.

The cases of $\text{PLOSTT}(\text{NB}, \text{SW})$ can then be represented as:

$$\text{Case}(M), \text{Case}(M+1), \text{Case}(M+2), \dots, \text{Case}(SW)$$

Using equation (5.10), they can be rewritten, respectively, as:

$$C_{M-1}^{M-1}, C_M^{M-1}, C_{M+1}^{M-1}, \dots, C_{SW-1}^{M-1}$$

In fact, knowing that: $M-1 < M < M+1 < \dots < SW-1$

the cases of $\text{PLOSTT}(\text{NB}, \text{SW})$ can be arranged as follows:

$$C_{M-1}^{M-1} < C_M^{M-1} < C_{M+1}^{M-1} < \dots < C_{SW-1}^{M-1}$$

Note that: $CL_{SW}^M = C_{SW-1}^{M-1}$ gives all possible cases. So, the probabilities associated to the different $\text{PLOSTT}(\text{NB}, \text{SW})$ cases can be calculated as follows:

$$\frac{C_{M-1}^{M-1}}{C_{SW-1}^{M-1}} < \frac{C_M^{M-1}}{C_{SW-1}^{M-1}} < \frac{C_{M+1}^{M-1}}{C_{SW-1}^{M-1}} < \dots < \frac{C_{SW-1}^{M-1}}{C_{SW-1}^{M-1}}$$

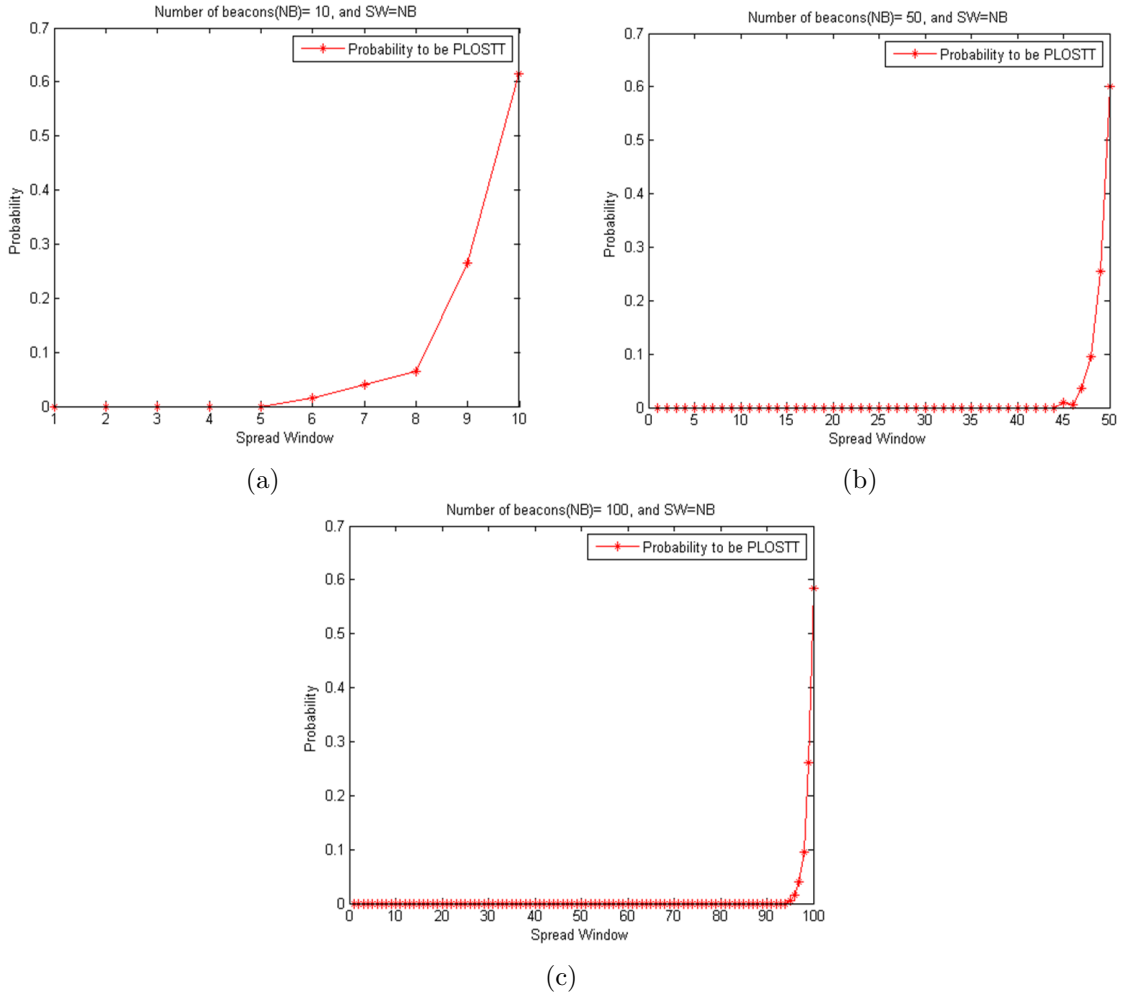


Figure 5.16: Probability of the STT numbers to be the PLOSTT for different numbers of beacons, and where $NB=SW$

And can be written, respectively, as:

$$Prob[Case(M)] < Prob[Case(M + 1)] < Prob[Case(M + 2)], \dots, Prob[Case(SW)]$$

The analytic study has proved that the case(SW), where the PLOSTT=SW, has the highest probability of happening. Figure 5.16 shows the result of different simulation studies performed with Matlab to confirm the analytic proof. In detail, it presents some examples which have been taken by setting $NB=SW$. All the graphs show that Case(SW) has the highest probability.

For a more general confirmation, it becomes necessary to calculate the analytic and the simulated **Average of Time Gaps Ratio (AvgTGR)** for different SW sizes, in order to generalize the results of Figure 5.16 Based on the equation (5.8), the prediction of the average time gaps ratio can be made as follows: $\forall SW \in SWSet, \forall NB \in NBSet$:

$$AvgTGR(SW) = \sum_{NB} \left[\frac{SW - HOP(NB, SW)}{SW} \right] / |NBSet|$$

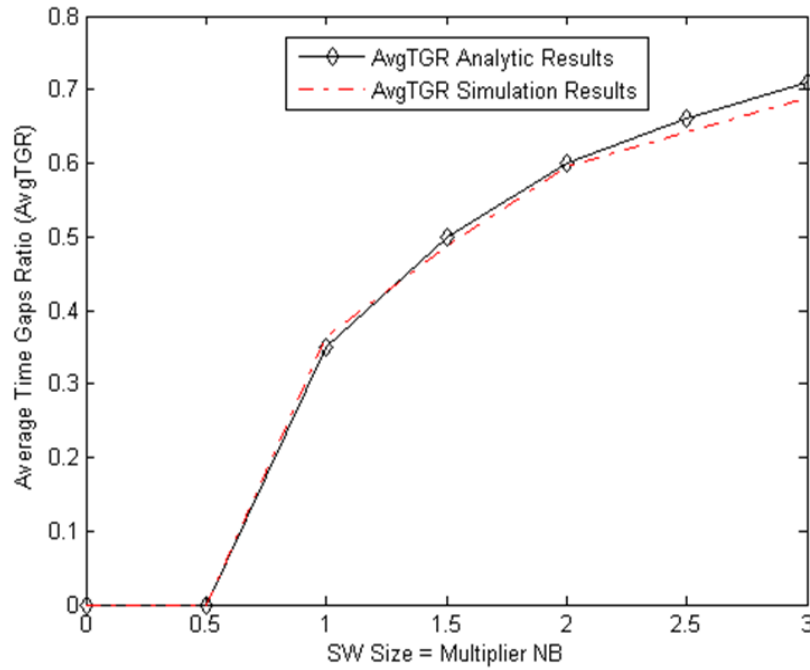


Figure 5.17: Impact of the size of the SW on the average time gaps ratio.

Figure 5.17 shows the impact of the SW size on the average results for the time gaps ratio. As expected, the size of the SW has an incremental impact on the time gaps. Finding the optimal SW size according to the number of contending beacons is the main objective of this work. In particular, it aims at finding the best trade-off between the beacons transmission contention and the time gaps.

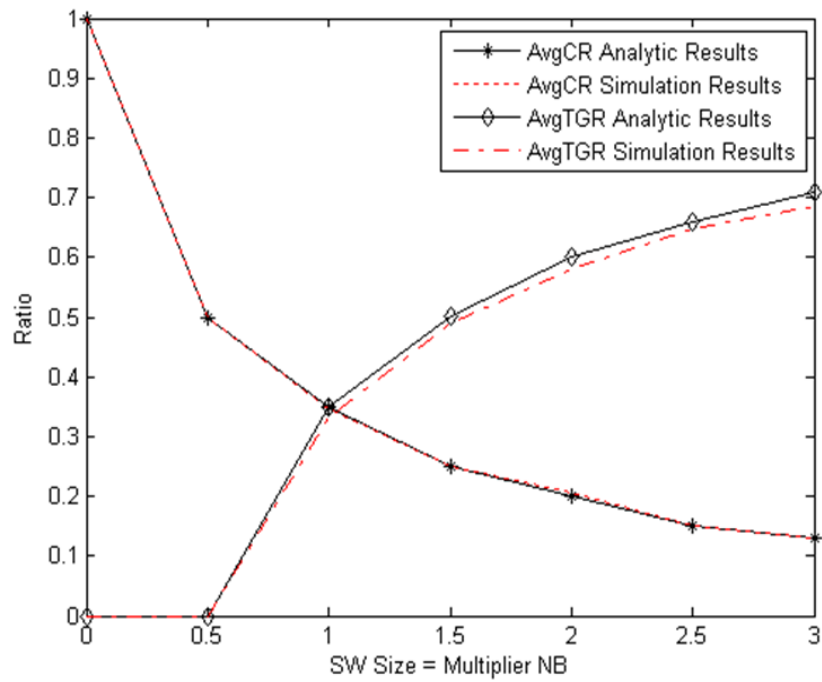


Figure 5.18: Impact of the size of the SW on the average time gaps ratio, and on the average contention ratio.

To that aim, the Figure 5.18 simultaneously shows the results of the AvgCR and AvgTGR graphs, allowing us to see the impact of the SW size on both ratios. As shown, when the size of the SW is equal to one STT ($SW = 0 \times NB = 1$), there are Time gaps (AvgTGR=0), but the contention is at its highest level (AvgCR=1). When $SW = 1/2 \times NB$, there are no Time Gaps, but the contention is reduced to the half. If $SW=NB$, there is a 30% of time gaps in the SW, and the contention is reduced to 30%. After that, as the size of the SW gets bigger, the contention decreases, but this improvement comes at the expense of increasing the time gaps. The analytic results show that the optimal size of the SW when it is equal to the number of vehicles in two hops rang of each other where both direct and hidden collisions are possible.

5.5 Simulation study

5.5.1 The Simulated protocols

This section presents the MAC protocols to be compared with the CSSA MAC:

5.5.1.1 S-ALOHA and CSMA

CSSA MAC protocol is considered as a combination of the advantageous of the two MAC mechanisms S-ALOHA and CSMA. The random beacon is spread over space using S-ALOHA, and the random back-off before beacon transmission using CSMA. In order to show the efficiency of combining these two advantageous against the different type of collisions,

It is important to compare CSSA MAC with the original version the two protocols. Note that, with CSMA the contention window (CW) used is the same as used in the 802.11p standard.

On the other hand, the S-ALOHA use the same spreading window (SW) used by CSSA MAC but with the immediate transmission and without backoff mechanism. With the S-ALOHA the slots are randomly and uniformly chosen over the same spreading window (SW) used by CSSA MAC. The slot is called a singleton if it contains only one packet but if it contains more than one packet, a collision will be happen because of the immediate transmission and without the backoff mechanism.

5.5.1.2 ASDM (Adaptive Space-division Multiplexing)

The most robust slot allocation for TDMA mechanism is the space division multiplexing. ASDM protocol [128] is one of the methods of this category. It is capable to adjust automatically the time slot allocation in response to changes in vehicle densities without exchanging control messages which consume the bandwidth.

The slot allocation in SDMA approaches consist of dividing the roadway into cells that can contain at most one vehicle using a mapping function that maps cells to time slots, and assignment rules that specify which of these time slots a vehicle is authorized to be used. The primary goal of the mapping function is to ensure that the time slots assigned to a vehicle are as evenly distributed as possible without any infrastructure. It is defined as the mathematical function that assigns each of these cells a unique time slot. Moreover, it reuses time slot assignments subject to the constraint that no two cells within a predefined range of each other be mapped

to the same time slot.

The result of this function is a slot-space map calendar calculated by each vehicle with same way.

The assignment rule in ASDM supposes that vehicles may transmit in the time slot assigned to the cells that they occupy. Therefore, each vehicle is able to obtain its GPS position information and also the positions of the preceding vehicles through the receipt of periodic messages from each other. A vehicle could accurately determine its own position with a combination of GPS and the positions of the neighbor vehicles. This method is easy to implement in highway scenes. However, it is difficult to divide roads into segments under the city scenarios where the topology of the roads is complex, therefore, the infrastructure is used in order to distribute a Slot-Space map calendar which contain the slot number of each cell in the road.

The direct and hidden terminal problem can be reduced by adopting ASDM which decreases the collision rate. However, this advantageous comes at the expense of some drawbacks and challenges that need to be considered which are the implementation cost of the infrastructure in the cities and the necessity of using the GPS and also the important wasting time, as showing in Figure 5.19.

Another big challenge for ASDM is the accuracy of the slot-space map calendar where the geographic cell length has to contain at most one vehicle. This accuracy depends to the efficiency of the mapping function and the accuracy of vehicle position using GPS. In order to shown the impact of this challenge on the performance of ASDM protocol, two versions of the slot-space map calendar is used in the simulation efficiency. The high accuracy where the Cell length equal to 5 meters (Cell.length = 5m) and the low accuracy where the Cell length equal to 10 meters (Cell.length = 10m).

The objective of the comparison with ASDM is to show the ability of CSSA MAC in decreasing the hidden terminal problem as well as the ASDM with the elimination of its drawbacks and challenges.

The five MAC protocols under consideration are summarized in Table 5.1.

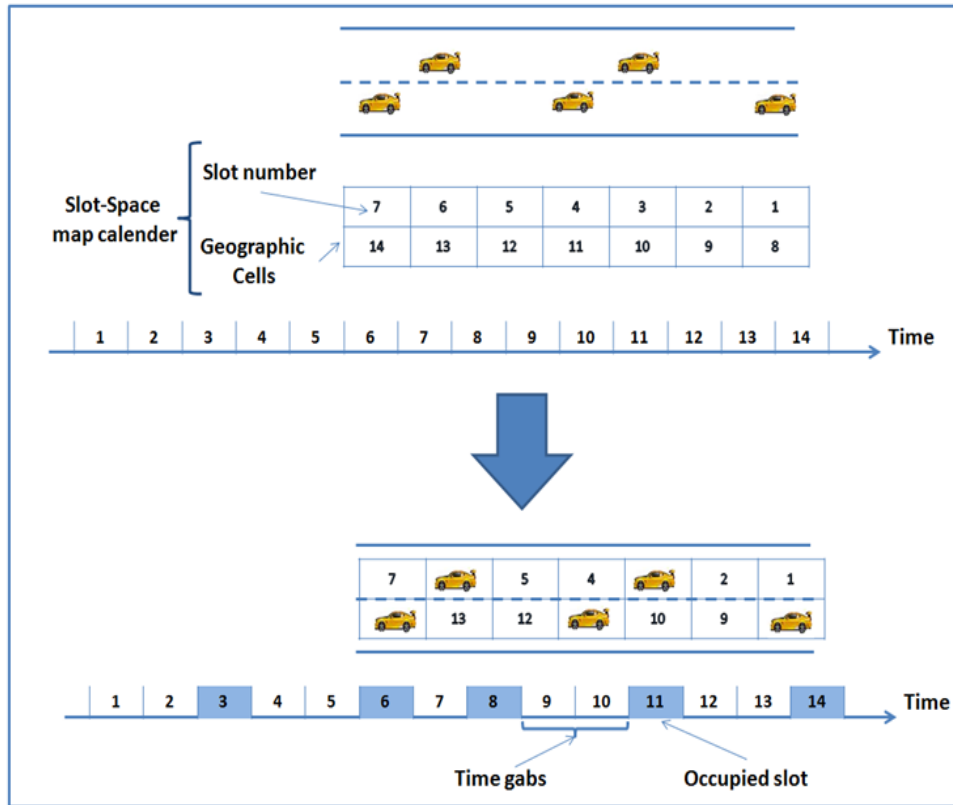


Figure 5.19: The slot assigning process with ASDM protocol.

Table 5.1: The simulated protocols

Protocol	Abbriviation
CSSA MAC with SW = LD	CSSA MAC
S-ALOHA	S-ALOHA
CSMA	CSMA
ASDM with low accuracy Cell=10m	ASDM_Cell=10
ASDM with high accuracy Cell=5m	ASDM_Cell=5

5.5.2 Simulation parameters

To evaluate the performance of the CSSA protocol in comparison with the other MAC protocols in broadcasting periodic safety messages which are generated continuously, at each node in the simulations. Computer simulations are conducted using the network simulator NS-2 and all the contender protocols work over the physical layer of the standards IEEE 802.11p. It employs the OFDM physical layer for the 5 GHz band where the carrier frequency of 5.89 GHz which represents the center frequency of the DSRC channel 178 (the CCH). On the other hand, the IEEE 802.11p employs the EDCA scheme, which assigns any packet to one of four different access categories (ACs). For the current study, the periodic safety message is assigned to the second-highest priority of the four access categories which is the AC Video. This priority uses a CW_{min} equals to seven physical slots ($CW_{min} = 7$). In the future work, the co-existence of the two safety applications will be studied, the first second-highest priority will be assigned to the event-driven. All vehicles generate 300 bytes long packets including all protocol overhead transmitted with a transfer rate of 3Mbit/s . In addition to the guard time (T_{Guard}), the AIFS period and the minimum Contention Window (CW_{min}) interval the duration of the time slot will be equal to one millisecond. Both communication range and carrier sensing range equal to 300 m for free space propagation. Table 5.2 summarizes the network parameters.

Table 5.2: Network parameters

Parameter	Value
SIFS, TSIFS	$16\ \mu s$
Physical slot, ∂	$9\ \mu s$
CW_{min}	7
CW_{max}	Never used (broadcast only)
Simulation duration	50 seconds
Transmission range	300 m
Data rate	3 Mbps
Time Slot duration	1 ms

The highway is the simulation scenarios considered for the performance evaluation of the contender protocols which are generated by the mobility generator IMPORTANT [79]. It is a segment of 1000 meters with two-opposite vehicle traffic highway and two lanes each one where the vehicles can communication with each other without obstacles. The vehicle moves with a variable high speed drawn from normal distribution and the number of vehicles on the highway remains constant during the simulation time. When a vehicle reaches one end of the highway segment, it re-enter from the other end. This scenario is the best one to evaluate the efficiency of the protocols against the merging collisions under low and medium density of vehicles.

Figure 5.20 Shows a representation of the simulated highway scenario where the black and white triangles represent vehicles moving in opposite directions.

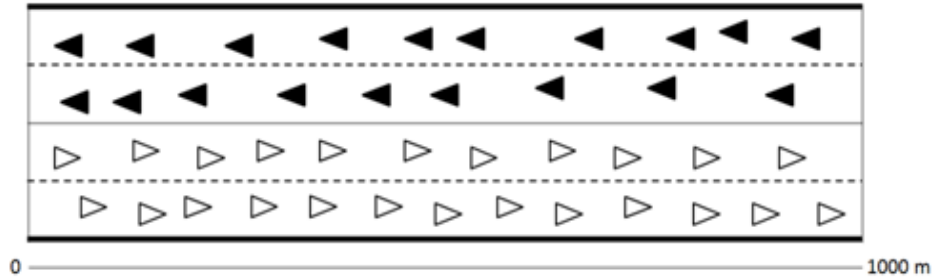


Figure 5.20: Representation of the simulated highway segment.

For the scenario under consideration, all the transmitted packets are periodic broadcast packets, the wireless channel is ideal, and the only source of packet errors is the transmission collision. All vehicles are distributed uniformly and independently on the lane. The communication links are assumed to be symmetric and each vehicle in the network has the same and fixed communication range R and each vehicle occupies a space of $(V.length)$.

The parameter named Two-Hop Cluster (THC) is defined as the virtual area of the road which can be covered in two-hops.

The length $2R$ is the maximum length of road that a THC can cover on the highway segment, so THC must satisfy the equation (5.11), where (L) is the number of lanes in the highway.

$$THC.H = (2R \times L) \quad (5.11)$$

Let us define the $THC.SpacesAvailable$ as the maximum number of vehicles that can reside in a THC (or the capacity of THC in term of number of vehicles). It can be calculated according

to the length of a vehicle ($V.length$), as presented in equation (5.12).

$$THC.SpaceAvailable = THC/(V.length) \quad (5.12)$$

So that, the $THC.SpaceOccupancy$ (THCSO) is defined to indicate the ratio of the number of vehicles present per THC, as shown in the equation (5.13).

$$THC.SpaceOccupancy = NumberOfVehicles/THC.SpaceAvailable \quad (5.13)$$

On the other hand, The $THC.SlotsAvailable$ is defined as the maximum number of the available time slots per THC for the ASDM protocol. It represents the maximum of cells in the slot-space map calendar. In order to eliminate the access collision risk (direct and hidden collision), it is necessary to use a fixed time frames to be equal, or superior, to the size of $THC.SlotsAvailable$. It can be calculated according to the length of a cell, as presented in the equation (5.14).

$$THC.SlotsAvailable = THC/(cell.length) = FrameSize \quad (5.14)$$

Note that the slot allocation will be highly accurate when the Cell length equals to vehicle length ($Cell.length = 5m$). In a contrary, it will have a low accuracy when the Cell length is higher than the vehicle length ($Cell.length = 10 m$), because it may happen that two vehicles occupy the same cell.

The slot frame size (or the number of slot per frame) is equivalent to the number of slot between the inter-transmission times of the periodic packets. From that, the packet transmission rate per second (r Hz) can be calculated, as shown in the equation (5.15).

$$r = 1000/FrameSize \quad (5.15)$$

In the current study, the frame size is chosen has to be superior or equal to the maximum number of time slot available for THC. So for a $FrameSize$ equal to 500 slots the packet transmission rate will be 2 Hz .

Note that the simulation results of the performance metrics do not reflect only the THC area but they represent the average of the data generated from all vehicles of the network which is

1 km. The reason is to show the impact of all kind of collisions, the access and the merging collisions. Table 5.3 summarizes the network and the scenario parameters.

Table 5.3: The scenario parameters

Parameter	Value
Road size	$1,6 \times THC (= 1Km)$
Number of lanes	4
Vehicle length (V.length)	5 m
Speed of vehicles	80 – 120 Km/h
THC.SpaceAvailable	480 vehicles
Number of vehicles / THC	50 to 300 (step=50)
THC.SpaceOccupancy (THCSO)	0.1 to 0.6 (step=0.1)
THC.SlotsAvailable	240 slots/THC (Cell=10) And 480 slots/THC (Cell=5)
Slot/frame	500
Transmission rate ($\approx$ Frame size)	$2Hz \approx 500slots$
Time of simulation	100 s

5.5.3 Performance metrics

Seven different performance metrics have therefore been selected for evaluating the performance of the simulated protocols. These performance measures reflect both specific MAC features as well as the overall C- ITS performance. The following performance metrics are considered:

1. **Average medium access collisions probability (AMACP)**: the total number of collisions detected by the receiving antenna, divided by the total number of messages sent within the communications range (the same collision, when detected by several vehicles, is considered as a single collision).
2. **Average successful Medium access probability (ASMAP)**: the probability of having access to the channel without direct collision. It refers to the total number of beacons successfully sent, divided by the total number of the beacons generated by the vehicles.
3. **Average Fairness of Access Ratio (AFAR)**: The concept depends on the definition of fairness, on the premise that all nodes should be able to send the same number of messages in a given time. It measures the ability of vehicles to transmit similar numbers of beacons, and having equitable chances when accessing the channel (equitable medium access probability).
4. **Packet Delivery Ratio (PDR)**: refers to the fraction of correctly received beacons by a

given vehicle over the total number of transmitted beacons from its neighbors. This metric has a relation with the reception rate of broadcast traffic which depends usually on the mutual distance between transmitter and receivers where the broadcast traffic sources are uniformly distributed and without retransmission.

5. **Average Discovery Ratio (ADR)**: The discovery range is defined as the longest distance between a transmitter and a receiver which is able to receive packets with a given packet reception rate. The ideal discovery ratio should have the highest packet reception rate and remains constant as the density increases for the whole transmission range.
6. **Average Packet Inter-arrival Time (APIT)** (or Real Update Delay): This metric is very used to evaluate MAC effectiveness under DCC mechanisms. It is exclusively related to periodic traffic (CAM) to define the average time between two consecutive successfully received packets from the same sender. Thus, it can be used to calculate the probability that this average time exceeded a certain threshold.
7. **Average Time Gaps Ratio (ATGR)**: represent the average of the total empty time slots between the occupied slot (collisions or successful transmission) that each vehicle can perceive during given time frame divided by the total period from the beginning of the frame to the last occupied slot in the frame.

Note that, Each of the metrics is measured for the entire simulation area, and then multiplied by 0,6 which represents the size of THC compared to the highway scenarios of one kilometer.

5.5.4 Simulation results

The first metric to be studied is the average medium collisions probability (all kind of collisions, access and merging collisions which can be direct or hidden) for the protocols under consideration, as shown in Figure 5.21 As expected, the CSMA of IEEE 802.11p standard shows a considerably high probability of medium collisions when compared to other protocols and it increases as the density of vehicles increases. This verifies the inefficiency of the medium access used by the standard in avoiding the medium collisions especially under high density of vehicles. The S-ALOHA illustrates an improved results compared to the standard thanks to the spreading technique of the STT (Start of Transmission Time) of Beacons messages which

reduce the contention in the medium. The CSSA MAC protocol achieves a less rate of medium collisions than that of the S-ALOHA protocol by 40% under a density of 300 vehicle per THC. This reduction is due to the combination of the medium access method of CSMA/CA and the spreading of STT technique used by S-ALOHA protocol. Moreover, the plot of CSSA MAC protocol, in general, remains constant for almost densities which ensure the scalability factor. Whereas, The SDMA_{cell}=10 protocol suffers from the medium collisions and still increasing as the density increases. Note that, after a density of 120 vehcles per THC the SDMA_{cell}=10 protocol show a bad performance than CSSA MAC protocol. This is because of the inaccuracy of its slot-space map calendar which uses a large cell. Therefore, more than one vehicle can take the same time-slot and they can send at the same time without backoff mechanism. Note that, the SDMA_{cell}=5 protocol has better performance than the CSSA MAC protocol for all densities while for a density equal to 300 vehicles per THC the SDMA_{cell}=5 protocol starts to perform almost the same as the CSSA MAC protocol. However, its performance decreases with the increase of the density of vehicles due to its inability to handle the merging collisions caused by the mobility of vehicles.

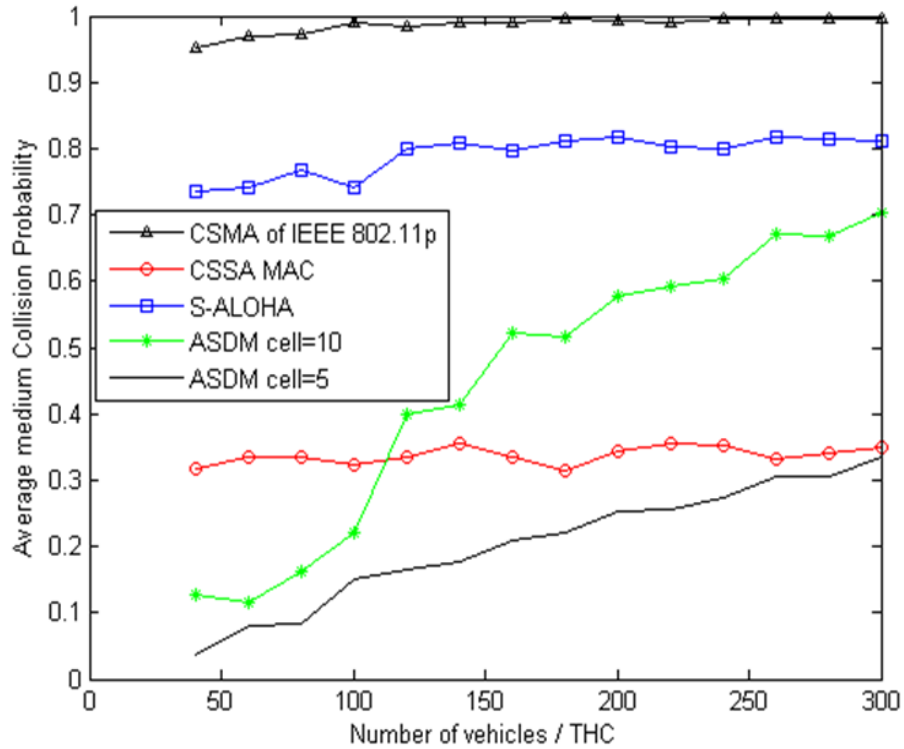


Figure 5.21: The average medium collision probability.

Figure 5.22 shows the average successful medium access probability for the MAC protocols

studied. The objective of this metric is to demonstrate the ability of the studied protocols to access the channel successfully and to avoid the direct access collisions between the vehicles within the range of each other. The hidden access collisions are not considered because they do not have any influence on this metric. The CSSA and SDMA_{cell=5} protocols have almost the same probability of medium access and they provides a stable value for different densities of vehicle. These values represent also the highest probability compared to the other protocols. Note that the S-ALOHA protocol provides a low access probability compared to the CSSA and SDMA_{cell=5} protocols, and also it shows a stable access value no matter the density of vehicles. This stability is due to the message spreading mechanism used by both CSSA and S-ALOHA. The CSMA of IEEE 802.11p protocol achieves the lowest probability of medium access which decreases as the density of vehicles increases. As expected, the ASDM_{cell=10} protocol shows a considerably decreasing probability of medium access when compared to the previous protocols, despite the fact that it uses the slot allocation of SDMA approaches. Its performance trends towards the CSMA behavior as the density increases, due to the low accuracy of the Cell length which equals to 10 meters and the lack of protection mechanism against simultaneous transmissions by nearby vehicles which reside in the same cell.

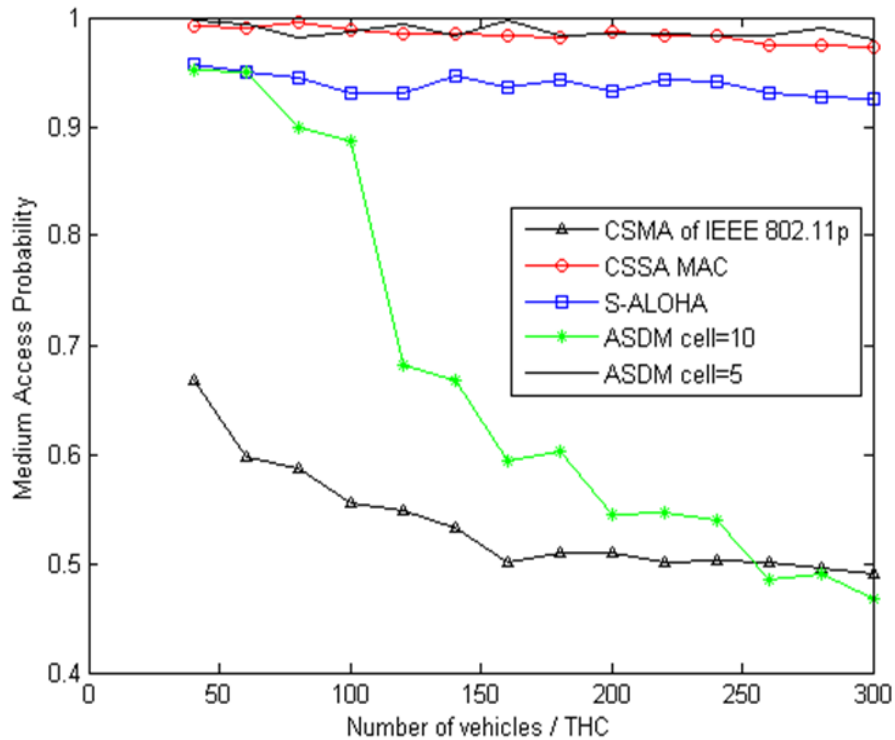


Figure 5.22: The average successful medium access probability.

The Average Fairness of access ratio is shown in Figure 5.23 for all the protocols. It can be seen as the equivalence of medium access probability between the contender vehicles. For that, the highway segment is divided into 30 equal zones and the average medium access probability of the vehicles which reside in each zone is calculated. Note that the density taken is 300 vehicles per THC which represent the worst case scenario. It is clear in the graphs that the protocols ASDM_cell=10 and CSMA of IEEE 802.11p provides a large relative difference of average medium access probabilities between the zones which prove that they are far to be faire in medium access between the contender vehicles. The reason is that these protocols suffer from collisions under the high density of vehicles. On the other hand the S-ALOHA protocol reveals a near relative difference in average medium access probabilities due to the spreading access strategy that reduces the probability of collisions between vehicles. Unlike the previous protocols, ASDM_cell=5 have very close relative difference in average medium access probabilities, thanks to its high accuracy in slot time distribution which reduce the rate of direct access collisions. The CSSA MAC outperforms the other protocols and shows a high fairness of access between the contender vehicles due to its medium access strategy which combines the spreading of time access and the use of backoff mechanism.

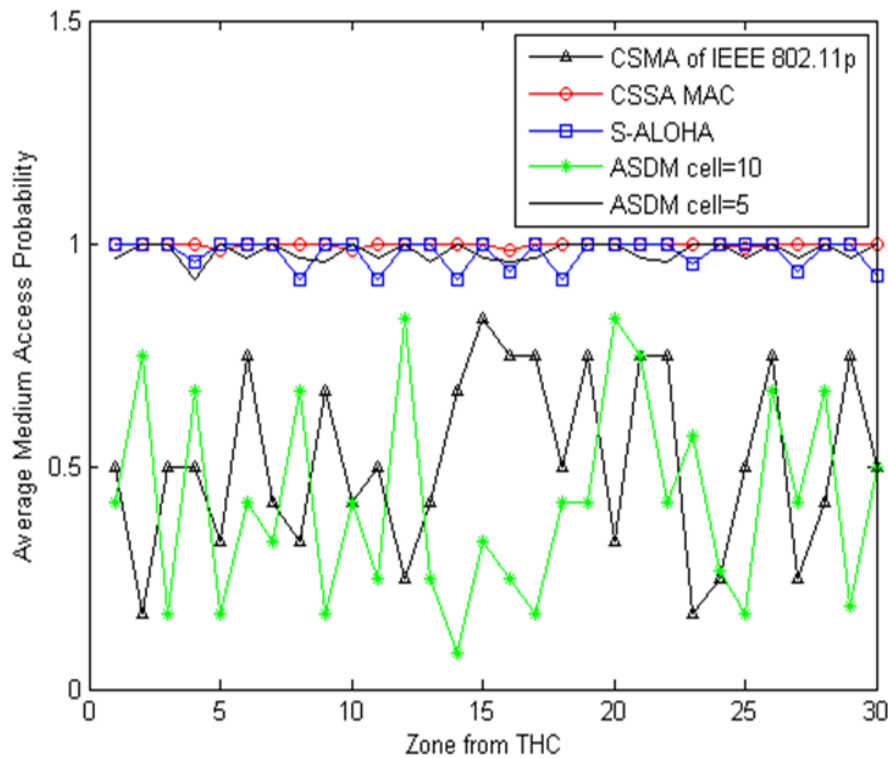


Figure 5.23: Fairness of medium access probability for a density of 300 vehicle per THC .

Figure 5.24 Shows the average Beacon Delivery Ratio (BDR) for the contender protocols. As for IEEE 802.11p, the BDR decreases rapidly as the traffic density increases, and the majority of transmitted messages are lost since collisions are taking place frequently. The S-ALOHA protocol shows better results compared to the IEEE 802.11p, because it generates a less rate of access collisions. It can improve the BDR by 27% than that of the IEEE 802.11p standard protocol when the density of vehicle is upper than 120 vehicles per THC. The reason is that, the IEEE 802.11p protocol suffers from the famous “start-of-interval contention” at every beginning of the CCH interval when the entire vehicle start sending at the same time. This situation generates a huge number of access collisions which adversely affects the Beacon Delivery Ratio. This kind of problem does not exist with the S-ALOHA protocol which employs the spreading of access time technique. The CSSA MAC protocol can improve the BDR, compared to The S-ALOHA, by 40% for a density higher than 120 vehicles per THC and as always it ensures a constant rate for all densities. The superiority of CSSA MAC is due to the combination of the backoff technique used by the CSMA protocol with the spreading of the transmission access time. This combination gives the protocol an addition chance to avoid the medium collisions. The ASDM_{cell}=10 protocol performs slightly better compared to CSSA MAC for a density less than a threshold of 120 vehicles per THC. However, upper this threshold the CSSA MAC outperforms the ASDM_{cell}=10 protocol and the later starts decreasing as the density increases. This is because of its inability to handle the medium collision problem under a high density as mentioned before. Note that, the ASDM_{cell}=5 protocol provides a BDR which is lightly higher than that of the CSSA MAC under a threshold of 220 vehicles per THC. After that threshold, the results turn in favor of the CSSA MAC with a little enhancement. This outperforming is a result of the excess of medium collisions and this is despite of the high accuracy of the slot-space map calendar which uses a Cell length equal to 5 meters.

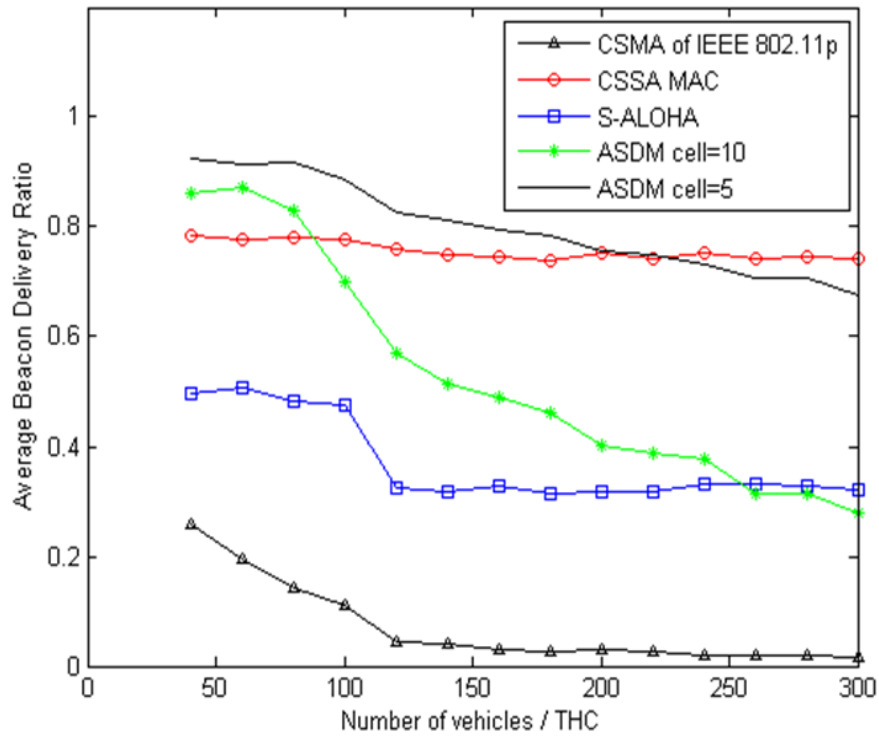


Figure 5.24: The average beacon delivery probability.

Figure 5.25 Shows the average discovery ratio of the different MAC protocol studied for a density of 300 vehicle per THC. It is also commonly referred to as the reception rate which measures the percentage of messages that can be successfully received by a receiver according to the distance from the sender. The x-axis is the discovery distance in inter-car spacing, and the y-axis is the discovery ratio. In general with all protocols, the plots demonstrate that the discovery ratio degrades as the distance between the sender and the receiver increases but with significant difference in performance. The discovery ratio of the CSMA decreases toward a 0% as it approaches to the borders of the transmission range. This is due to the inefficiency of the backoff mechanism against the high number of simultaneous transmissions by nearby vehicles, as well as the overlapping transmissions caused by the Hidden vehicles. It is noted that, the ASDM_{cell=10} protocol shows approximately 30% higher rate of discovery than the CSMA protocol when the distance between transmitter and receiver is larger than 50 meters. This is due to the fact that all transmissions in ASDM_{cell=10} are slot synchronized in space which reduce the risk of medium collisions. The ASDM_{cell=5} in turn improves the discovery ratio by approximately 40% higher than the ASDM_{cell=10} and the reason is in the accuracy of the Cell length of slot-space map calendar which is equal to 5 meters. This accuracy reduces the

medium collision risks more and more. The S-ALOHA protocol provides a discovery rate which is significantly higher than that of CSMA protocol by approximately 25% at the higher density but its ratio is slightly lower than the ratio provided by the ASDM_{cell}=10 protocol. This improvement due to the ability of the S-ALOHA protocol to spread the transmissions in time compared to the CSMA where the vehicles are more likely transmit at the same time under high density. So that, the benefits of spreading beacon transmissions in time comes into play. The CSSA MAC protocol shows a considerable enhancement of the discovery ratio by 25% compared to the S-ALOHA protocol and by an average of 5% as opposed to the ASDM_{cell}=5. This is due to the combination of the transmission time spreading with the backoff mechanism adopted by the CSMA protocol which reduces significantly the risk of collisions.

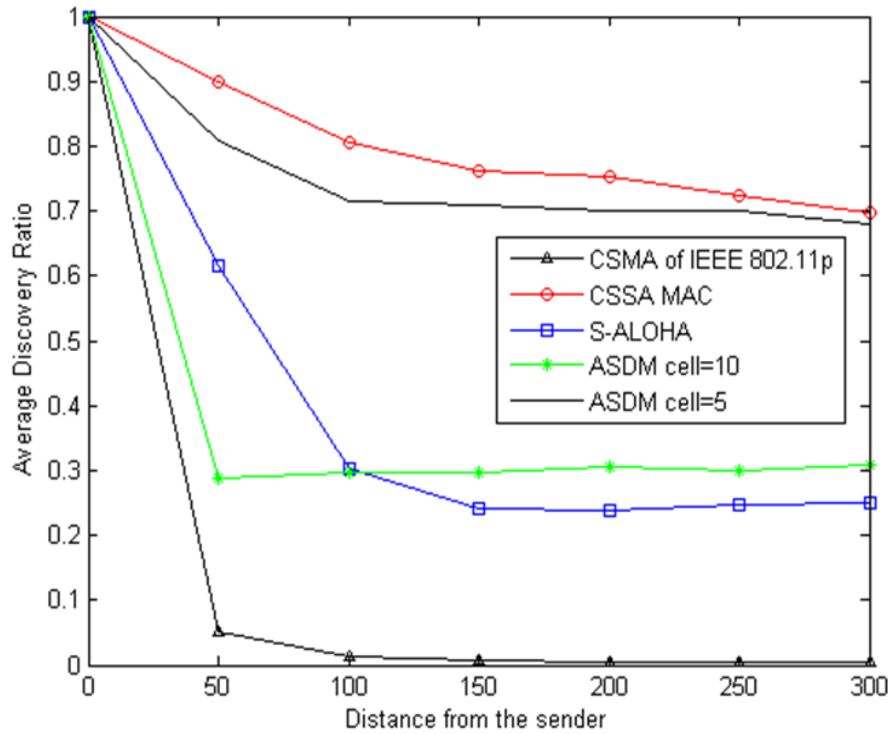


Figure 5.25: The average discovery range ratio.

Figure 5.26 Shows the average inter-arrival time of beacons which is also commonly referred to as the real Update delay. It is exclusively used to define the average time between two consecutive successfully received packets (CAM) from the same sender. The goal of this metric is to verify the ability of the studied protocols to avoid the collisions and to ensure an acceptable update delay of beaconing. The CSSA has almost the same update delay and it provides a stable value for different densities of vehicle. This is due to its ability to avoid collisions under different

densities thanks to the combination of the two mechanisms which are the transmission time spreading and the backoff mechanism. The two versions of ASDM_{cell} show a small update value compared to CSSA MAC, only under a certain density ratio, thanks to the time slot allocation technique but their graphs increase as the density increases. It is noted that, the ASDM_{cell}=5 protocol performs slightly better compared to CSSA MAC for a density less than a threshold of 250 vehicles per THC. This is due to the high accuracy of the Cell length of its slot -space map calendar which allow decreasing the risk of transmission collisions. The graph of ASDM_{cell}=10 start increasing compared to CSSA MAC protocol after a density ratio aquals to 120 Veh/THC and it still increasing until it shows approximately 33% higher value of update delay than the CSSA MAC protocol when the density of vehicles reaches the ratio of 300 Vehicle per THC. This is due to the inaccuracy of its slot-space map calendar under a high density. The S-ALOHA and CSMA protocols show a considerably increasing of update delay when compared to the previous protocols where one of them use the transmission time spreading mechanism and the other uses the backoff mechanism. Once again this metric confirms that the separation of these two mechanisms will increase significantly the risk of transmission collisions.

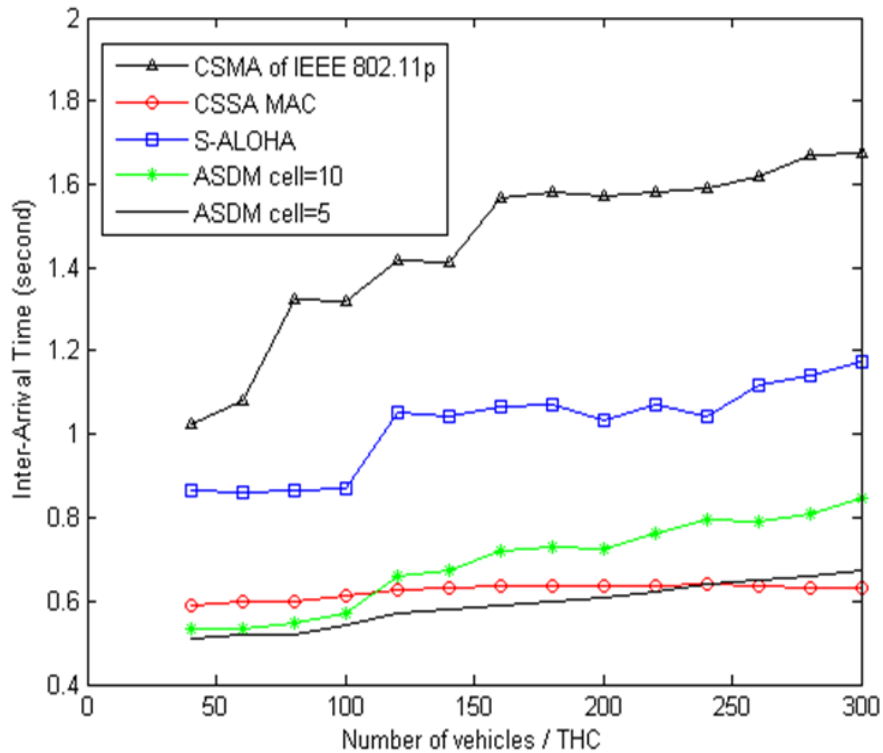


Figure 5.26: The average inter-arrival time .

Figure 5.27 shows the average time gabs ratio for the MAC protocols studied which represents

the average of the total unused time slots between the occupied slots neither for successful transmission nor for collisions. The objective of this metric is to demonstrate the ability of the studied protocols to ensure an optimal use of the channel. The CSSA and S-ALOHA protocols provide a stable value for different densities of vehicle. This stability is due to the access spreading mechanism where the spreading window size is equal to the number of beacons located in the two hope area. Note that CSSA MAC protocol provides low time gabs compared to S-ALOHA protocols and the reason is that CSSA MAC uses the backoff mechanism in addition to the access spreading mechanism. The combination of the two mechanisms reduces the risk of collision when two or more beacons are sent in the same STT and allows generating at least one successful transmission in the next STT beside the current one. Therefore, the number time gabs are reduce by 40% compared to S-ALOHA.

As expected, both ASDM_cell=5 and ASDM_cell=10 protocol shows a considerably decreasing of time gabs as the density of vehicles increases. The time slot allocation technique of these two protocols is based on the slot-space map calendar and the distribution of the time slots are depending on the vehicle's position over the whole size of THC. Therefore, the time gabs in the THC are reduced as the density increases. Moreover, there number depends to the size of cell used in the slot-space map calendar and logical the number of the time gabs increase as the cell size becomes small. This is explains the difference of time gabs between the two protocol by 40% of reduction.

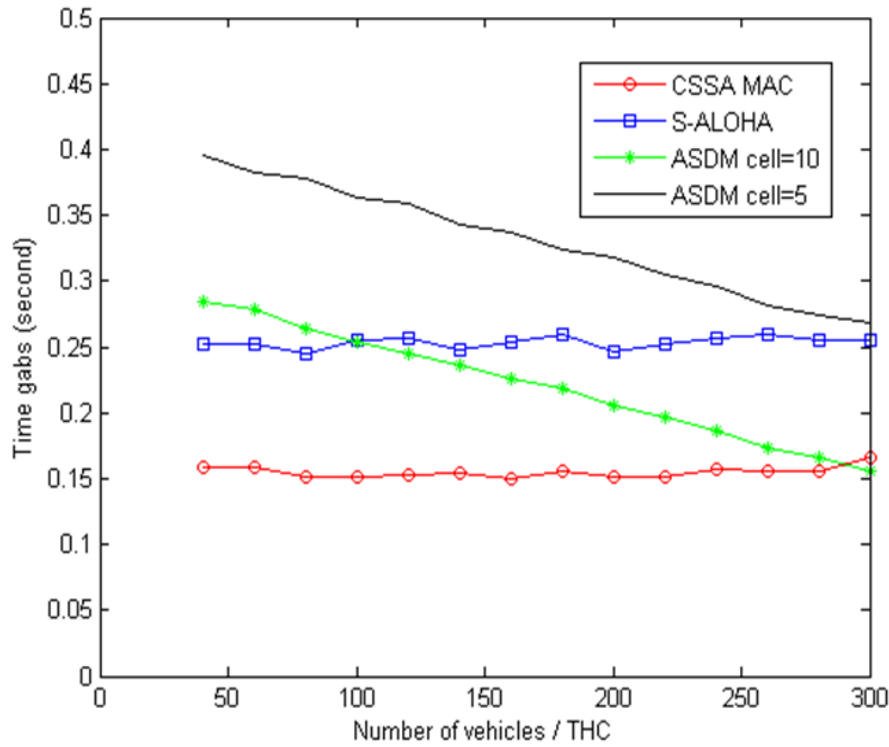


Figure 5.27: The average time gaps ratio.

5.6 Conclusion

This chapter discussed from a theoretical point of view the implications and the limites of using a low and fixed contention window as the only technique against the “start-of-interval contention” problem. The mathematical results show that the collision probability is significant higher at the beginning of the CCH interval and increases as the density increases.

Accordingly, this chapter presents the CSSA MAC, a novel MAC protocol based on CSMA and S-ALOHA for periodic safety messages in VANETs. The techniques employed by the protocol for accessing the CCH are explained and Mathematical analysis is presented to evaluate the performance of the CSSA MAC protocol and the impact of adjusting the SW which is the main parameter used by the proposed protocol to reduce the effect of the congestion problem on the CCH. Based on these analyses, the optimal value of SW for each local vehicle density is determined. To confirm and verify the effectiveness of theoretical results, a simulation study is performed in the next chapter based on a vehicle simulation network.

This chapter presents, also, computer simulations to evaluate the performance of the proposal called CSSA MAC protocol, in highway scenario, in comparison with different MAC protocol.

The Simulation results show that CSSA MAC provides a smaller rate of medium collisions and behaves in a significantly higher performance closer to that provided by $ASDM_{cell} = 5$ MAC protocol and outperforms the others. The later protocol is considered as one of the most robust contention-free medium access protocol. It uses the space division multiplexing as slot allocation mechanism for TDMA protocol. However, it is hard to be implemented due to the complexity of calculating the slot-space map calendar in the real road by using the mapping function that maps cells to time slots with the use of GPS position of vehicles. Moreover, the $ASDM_{cell} = 5$ MAC protocol causes a lot of time gabs in the CCH which is considered as a wasted time. The outperforming of the CSSA MAC protocol compared to the $ASDM_{cell} = 5$ MAC is in its ability to ensure a best trade-off between reducing beacons transmission contention and reducing the time gabs. Such a results confirm the efficiency of using a random spreading of the access times combined with the CSMA/CA mechanism, as a medium access strategy. In particular, it allows to avoid the start-of-interval contention at the beginning of each CCH, and to minimize the risk of collision using the CSMA/CA mechanism when some beacons select the same STT.

The CSSA MAC combines the simplicity of the contention-based protocol with efficiency of the contention-free protocols.

CSTD-MAC: CSMA with TDMA-like operation for VANET MAC

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6.1 Introduction

TDMA-based MAC protocol is promising to achieve better performances in terms of channel access control in VANets when compared to CSMA of the IEEE 802.11p. One of the TDMA challenging schemes is the difficulty to allocate time slots appropriately to the contending vehicles in a distributive manner. Some solutions have been proposed, as ADHOC MAC and VeSOMAC, however, they often results in heavy network control overhead, where they require that the vehicles have to exchange their frame information or list of neighbors. The contribution of this chapter includes the design of an in-band signalization, called CSTD MAC (CSmaTDms MAC) aiming to ensure a good allocation slots with less network overhead. The conducted initial simulations show that the proposed scheme performs better than CSMA of the IEEE 802.11p by reducing the rate of transmission collision.

The remainder of this paper is organized as follows. Section 2.1 presents the principal of the CSTD MAC protocol. Section 6.3 discusses the simulation work and the performances of the proposed protocol. Finally, Section 6.4 concludes the paper and discusses future works.

6.2 The CSSA MAC protocol

6.2.1 The main idea

The protocol is a novel medium access protocol named (CSma and TDma MAC) CSTD MAC, designed specifically for VANET to provide a periodic one hop broadcast service on the control channel. The proposal protocol aims to combine the advantageous of TDMA and CSMA medium access technics through a cross layer design, it works on the top of 802.11p with a little modification of its functionality, the upper layer ensure the time slot allocation process in distributed way (TDMA part) and the MAC layer wait for the slot and send the message with the CSMA fashion.

The CSTD MAC is developed on the top on the CSMA and gives it the ability to behave as TDMA fashion aiming to decrease the rate of transmission collision achieved by the CSMA of IEEE 802.11p. The main idea the CSTD MAC is the allocation of the time slot in distribution manner using an in-band signalization technique with a light control overhead, This new technic is different from the ones used by VeSOMAC and ADHOC MAC, which have some limitations as discussed in above.

CSTA MAC, in the beginning, does not require any prior signalisation; It starts working as a CSMA and progressively learns from the successful transmissions in order to migrate to TDMA-Like operation. All the vehicles maintain their lists of neighbors (LN), at the end of the each frame they analyse their lists to select an appropriate slot for the next frame, as shown in Figure 6.1. The selection process is dynamic and smart, if there is a collision or a change in the topology, the vehicle automatically select a new slot for the next frame, if not it keep using the same slot. The raison why the slot has to be changed with the change of topology is to satisfy the slot allocation requirements presented in the next section.

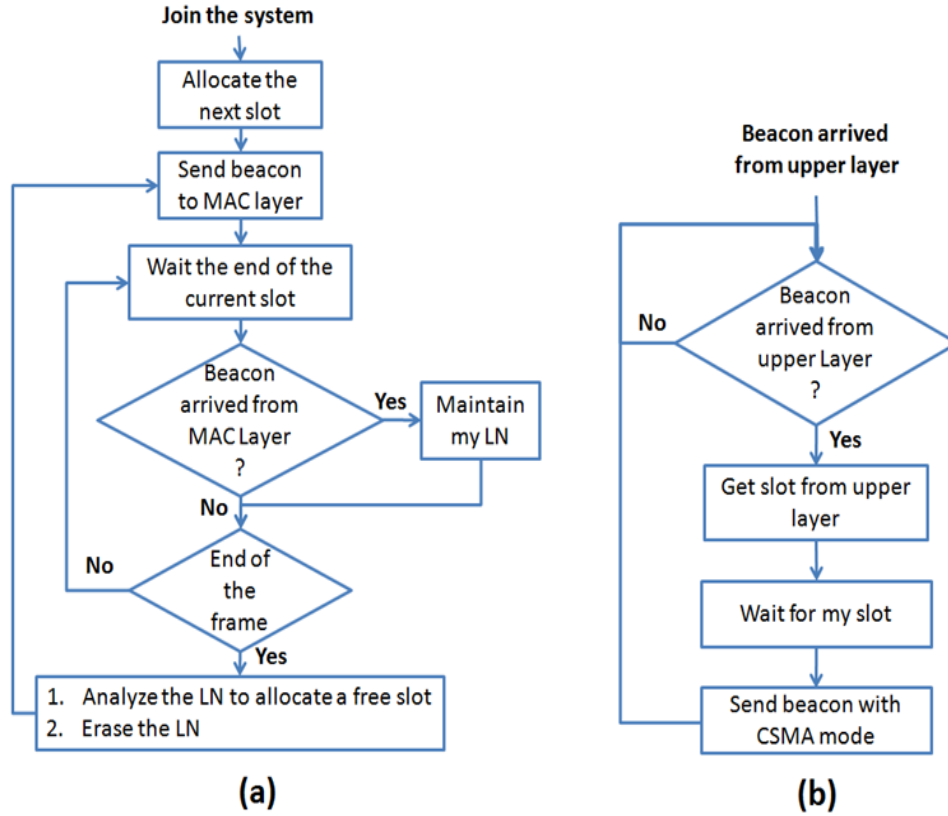


Figure 6.1: The CSTD MAC diagram: (a) the upper layer (b) the MAC layer.

6.2.2 System model

The system consideration is a set of vehicles in highway platoon moving in the same direction in which they have the same communication range R where the carrier sensing range is assumed to be the same as the communication range. The vehicles can be grouped in physical groups, denoted by pg , in which all of them can hear each other from one hop communication. It is supposed that the vehicles belonging to different pg cannot communicate with each other via one hop communication. Note that vehicles can belong to more than one pg leading to the case of intersection of two pg having at least one common vehicle, and the rest are hidden to each other, this cluster is called an Intersected Physical Cluster (ipg), such an environment is shown in Figure 6.2.

This arrangement of vehicles causes two types of transmission collisions; access collision and the merging collision. The access collision happens among vehicles trying to acquire the same time slots, it can be direct or hidden according to their membership to the same pg or ipg respectively. The merging collision occur among vehicles having a time slot when they become

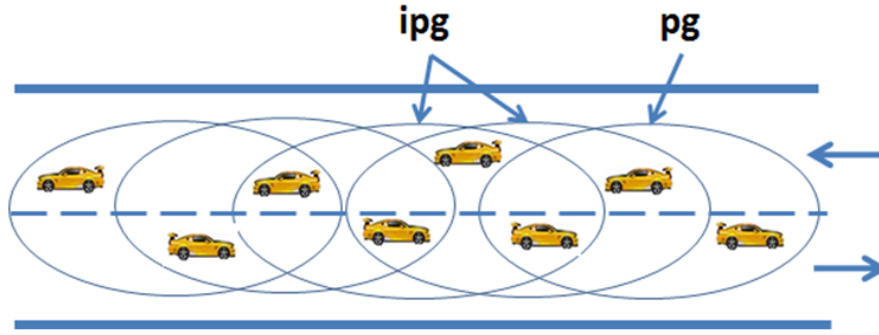


Figure 6.2: Vehicles in highway partitioned on physical cluster.

members due to the mobility, it can be also direct or hidden to the same pg or ipg respectively. Time is partitioned to frames consisting of a constant number of fixed duration time slots. The slot of the frame are accessed with the CSMA mode, all the vehicle need to backoff a random counter before accessing the selected slot, ensured by the guard time which has the same size as the CW, as shown in Figure 6.3 The rest of the slot represents the packet transmission time.

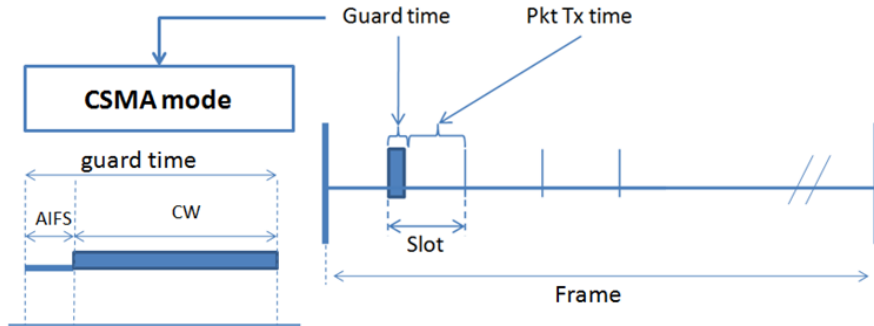


Figure 6.3: Frame and slot partitioning.

The system has one control channel CCH used for transmission of one kind of information: periodic driven safety messages (beacons), all the vehicles have the same size of beacon, the same frequency of sending and they start at the same time.

6.2.3 Slot allocation requirements

The slot allocation processin CSTD MAC needs to ensure that no overlapping between **One-Hop Neighbours (OHN)** and **Two-Hop Neighbors (THN)**, as presented in Figure 6.4. Accessing the slots with the CSMA mode, after acquiring a time slot, has the ability to minimise the merging collision probability when two or more vehicle become OHN or THN, the backoff mechanism

ensure the competition between an unexpected vehicle which has the same slot. To share the bandwidth efficiently among the vehicles, the reuse of slots is allowed between the **Three-Hop Neighbors (ThHN)**. The slots have to be ordered in sequence as the vehicles appear in a pg, so the whole group of slots used in a pg can be represented only by the minimum and the maximum slots, which facilitate the transmission of the hidden slots between the vehicles without exchanging the entire lists.

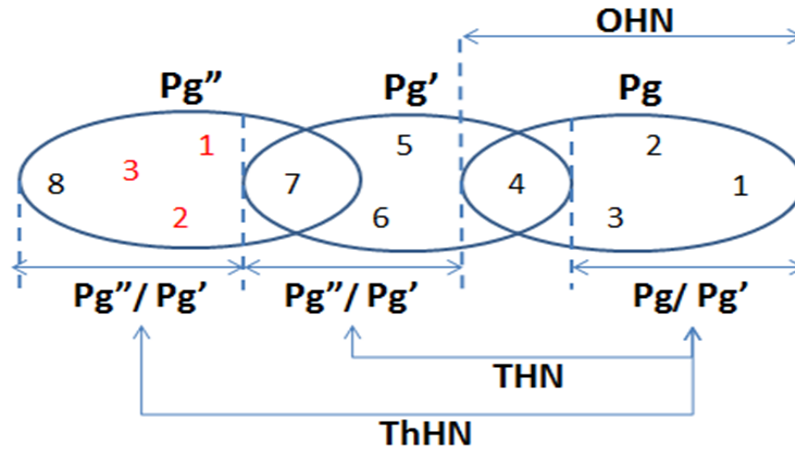


Figure 6.4: The neighbours map.

6.2.4 Packet format and Slot map extraction

It is necessary for each vehicle to know about the map slots of the surrounding to avoid using the slots of its OHN and THN and select a new slot or to reuse those of its ThHN, for that they have to exchange particular information allowing each other extracting their slot map. It does not necessary to transmit the list of all the neighbors as used in the majority of the TDMA protocols. In our proposal, the process is ensured by adding a light overhead packet to the hello message which contains only a three fields: (1) MySlot (2) the Minimum Two-Hop Slot (Min_THS) and (3) the Maximum Two-Hop Slot (Max_THS), as shown in Figure 6.5.

Payload	MySlot	Min_THS	Max_THS
---------	--------	---------	---------

Figure 6.5: Hello message format.

For each vehicle x the following lists have to be maintained, as shown in Figure 6.6 and Figure 6.7:

- $OHAS(x)$: the One-Hop neighbors Ahead Slots is the set of slots of one-hop neighbours ahead of the vehicle x , from which it received hello messages during the previous Frame.
- FUS : the Frame Used Slot is the set of all the used slots by the neighbors ahead of the vehicle x , $FUS=1,2,\dots, \text{Max}(OHAS(x))$.
- $THS(x)$: the Two Hop Slot is the set of used slots by the Two-hop ahead neighbors of the vehicle x , from which the Min_THS and Max_THS can be calculated, $THS(x)=FUS/OHAS(x)$.
- $ThHS(x)$: the Three Hop Slot is the set of used slots by the Three-hop ahead neighbors of the vehicle x , it can be transmitted by the y the farther neighbor ahead of the vehicle x , $ThHS(x)=[\text{Min}(THS(y)), \text{Max}(THS(y))]$.
- $RS(x)$: the Reuse Slots is the set of slots can be reused by the vehicle x from its Three-hop ahead neighbors, $RS(x)=ThHS(x)/OHAS(x)$.

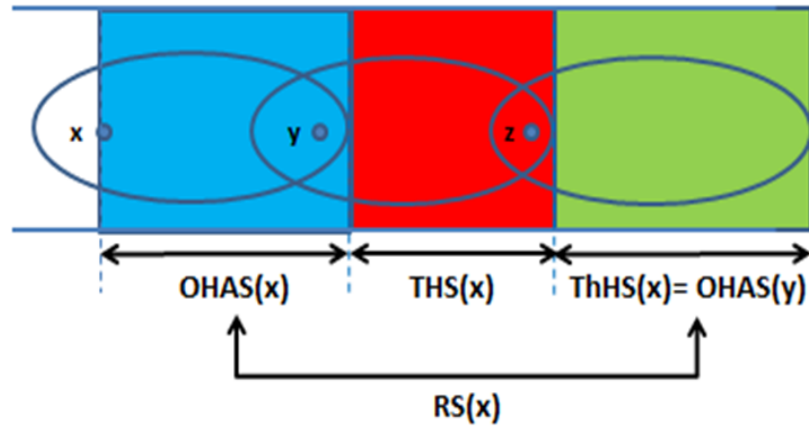


Figure 6.6: The slot map of the vehicle x .

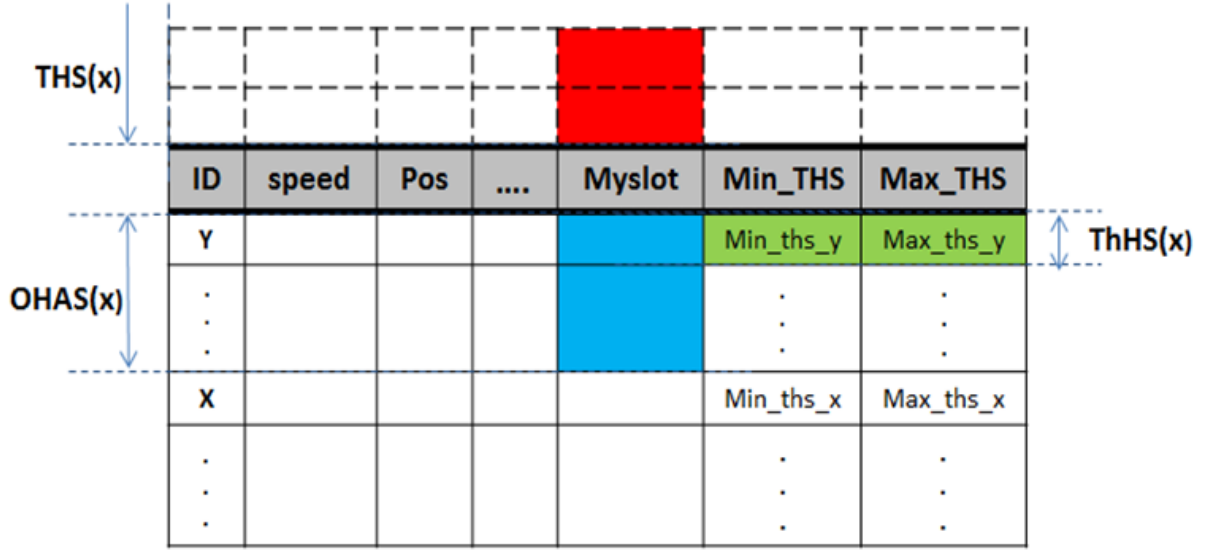


Figure 6.7: The lists of neighbours of the vehicle x.

6.2.4.1 Slot allocation mechanism

At the end of the current frame, each vehicle x analyze its list of neighbor to extract the slots map, after that it checks its own Reuse slot list $RS(x)$ to select a free slot for the next frame. If the $RS(x)$ is not empty, It selects the minimum one between the $\min(RS(x))$ and its current used slot, but if it is empty, it selects the slot after the maximum one of its direct slots ahead set $OHAS(x)$.

While the current slot

$$MySlot = \begin{cases} \min(\min(RS_{Fj-1}(x)), MySlot) & \text{if } RS_{Fj-1}(x) \neq \emptyset \\ \max(OHAS(x)) + 1 & \text{if } else \end{cases}$$

After allocating a free one, it is possible that the vehicles which do not hear each other yet will select the same time slot. That is why the guard time is used, before any transmission, to let the vehicles compete for that time slot using the CSMA mode, and also to minimize the risk of the emerging collisions caused by the high mobility. However, in spite of that, Collision can be happed if two or more vehicles select the same backoff value, so they try to get another one in the next frame, until a successful transmission will take place, In the case, the sender vehicle will be added in the LN of their neighbors. While the vehicle is present in the lists of their neighbors, the competition for its time slot is eliminated, until an emerging collision will

be happened caused by the joining of a new vehicle.

To understand the slot allocation process more clearly, some examples are shown in the following Figure which present a set of vehicles collaborating together to allocate the free slots in distributed manner. For that, Figure 6.8 shows the meaning of the four fields used in the example for each vehicle, which are: SlotNum, Max_HS, Min_HS and V_ID, having the following meaning respectively, the Slot number, the maximum hidden slot number, the minimum hidden slot number and the vehicle identifier.



Figure 6.8: The four field of the allocation process example.

Figure 6.9 shows a set of vehicles which did not here each other yet; they compete to get a free time slot, they all chose to get the first slot because their LNs are empty. To minimize the risk of collisions and to ensure the competition between the vehicles, a guard time is used let them backoff as the CSMA mode. However, collision can be happened if two or more vehicles select the same backoff value. In Figure 6.9, only the vehicle d sends its hello message successfully, in this case, it reserves the first slot for the next frame and it is added in the LNs of their neighbors a, b and c. While the vehicle d is present in the lists of their neighbors, the competition for its time slot is eliminated. In the frame 3, the vehicle a wins the second slot, in other hand b and c collide, therefore c will be added in the LNs of their neighbors as the vehicle d. At the end of the frame 3, the vehicles analyze their LN, a and d decide to reserve the first and the second slots respectively to ensure the order constraint and use them for the next upcoming frames, b and c will compete for the slot number three. The system will continue with this logic until it converges to a final state where the collisions will be eliminated as presented in the frame four.

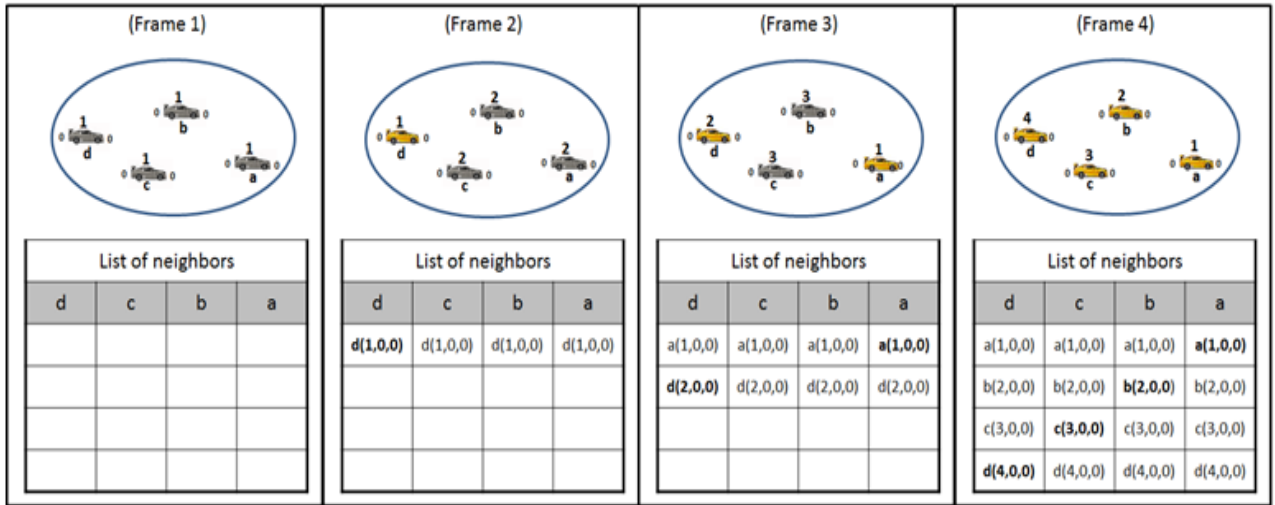


Figure 6.9: Example 1: Group of vehicles in the range of each other collaborating to allocate a free slots.

Consider that the vehicle e will join the group in the frame five, it is using the first slot because it is alone in its surrounding, as presented in Figure 6.10. When it joins the group from the beginning of the frame, it accesses to the channel at the same time as the vehicle a, therefore a hidden collision will be detected by the vehicles b, c and d. But when it hears its neighbors in the front and analyses their extra header, it can calculate its RS reuse slot list which is empty, thus it selects the successor of the maximum slot detected in its front and collision will be avoided. The same case is happened in Figure 6.11 when the vehicles f and g join the group.

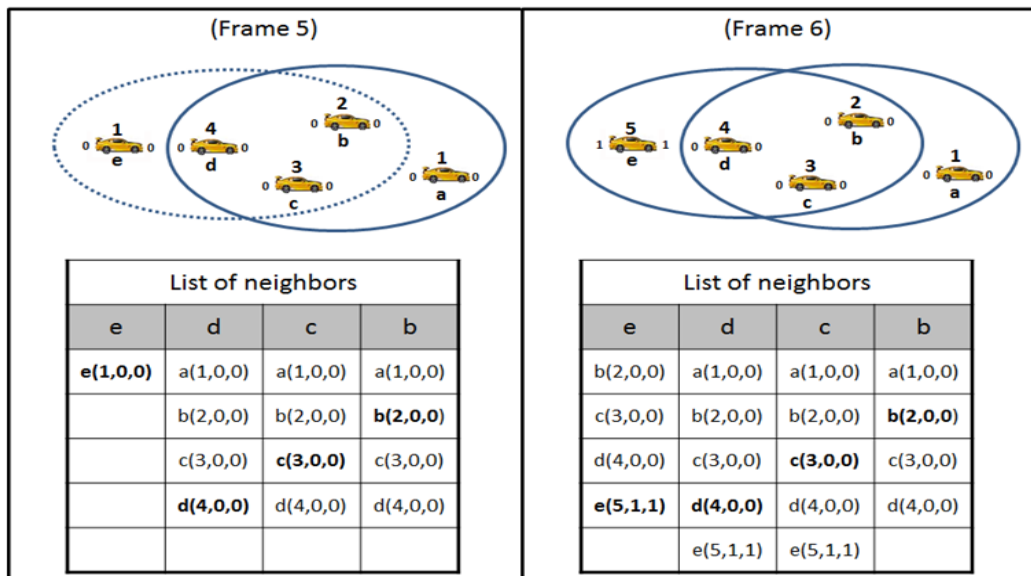


Figure 6.10: The four field of the allocation process example.

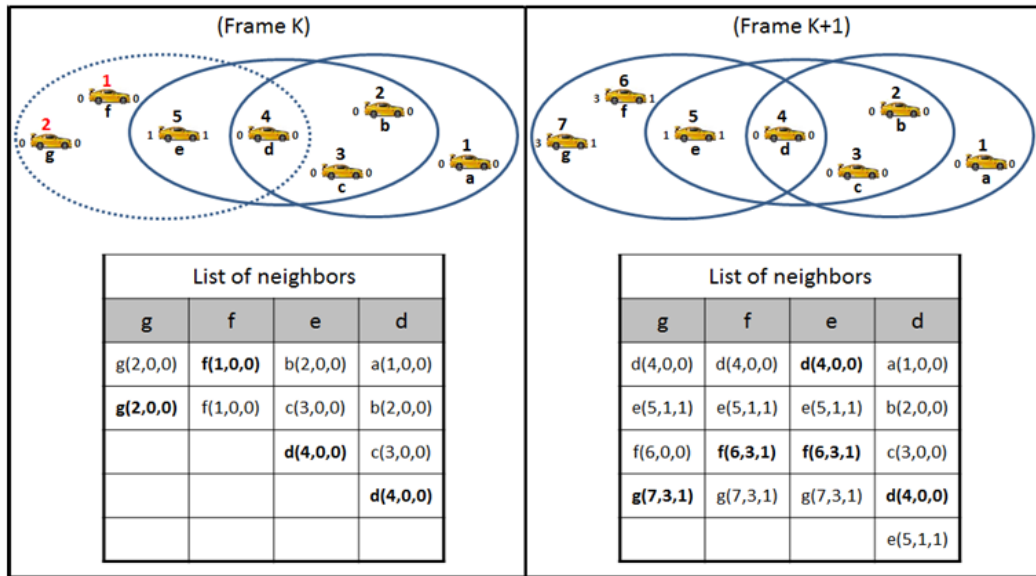


Figure 6.11: Example 2: The slot allocation when a new vehicles join the group.

The scenario in Figure 6.12 and Figure 6.13 presents how the slot can be reused when there is no overlapping. The vehicle h,j and k can reuse the slot number 1, 2 and 3 respectively, because that does not cause any collision with their neighbors ahead. In the other hand, the vehicles i and h cannot reuse any slot, they select a new ones.

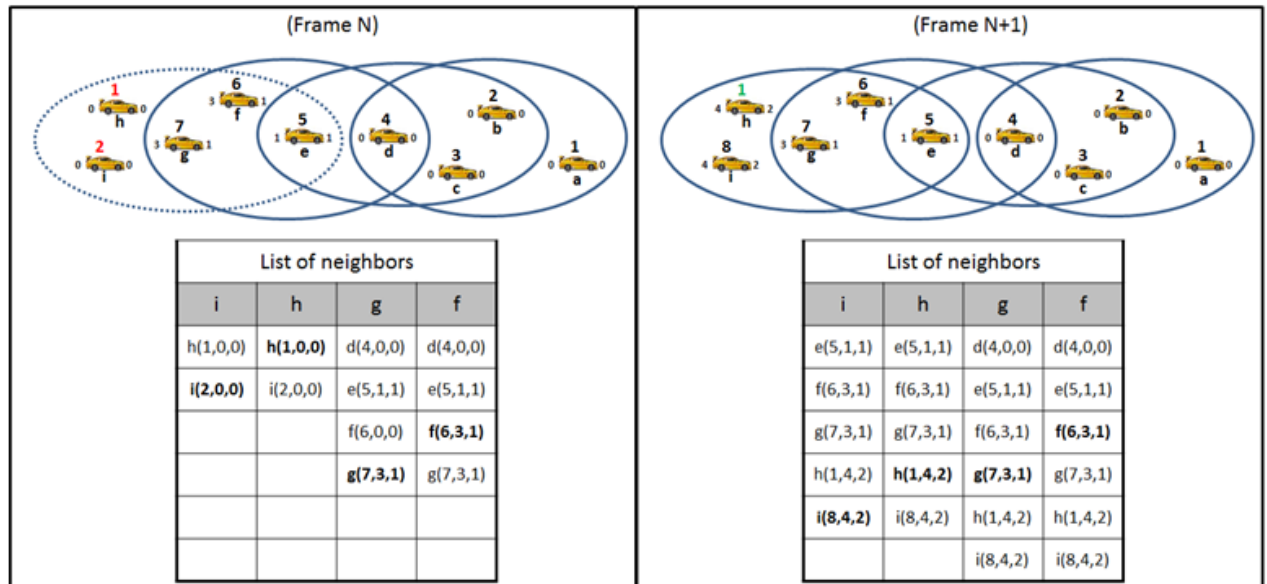


Figure 6.12: Example 3: The slot allocation when a new vehicles join the group.

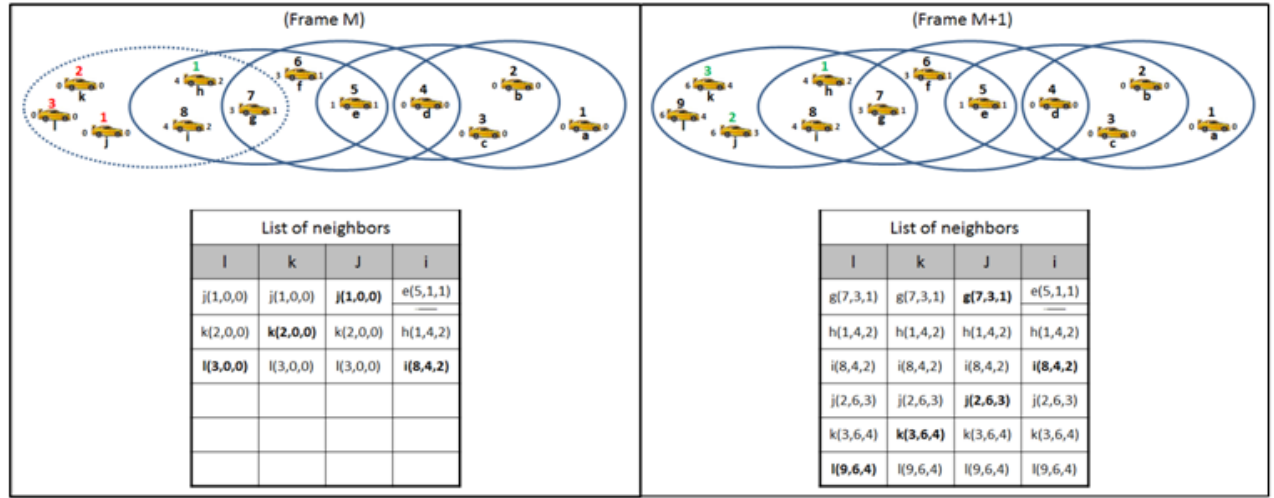


Figure 6.13: Example 4: The slot allocation when a new vehicles join the group.

After a short period of learning process, CSTD MAC can eliminate the direct and the hidden collisions between the vehicles of the physical groups. Due to the movement of the vehicles, the groups may overlap and cause some perturbation in the form of merging collisions which are impossible to be predicted, the system has the ability to overcome this perturbation and continues its TDMA-like operation.

6.3 Limitation of CSTD MAC

The learning ability of CSTD MAC gives the system the potential to reorganize after each topology change, however there is one case where the system cannot converge to the expected state. It is When two physical groups with the same number of vehicle overlap partially as the example shown in Figure 6.14, the overlapped vehicles cannot hear each other and the system stay unchangeable as long as the topology stay as it is. This problem can be resolved when the two groups merge completely and all the vehicles became in one group and being in the range of each other, in this case the system converge the same as the example presented in Figure 6.9.

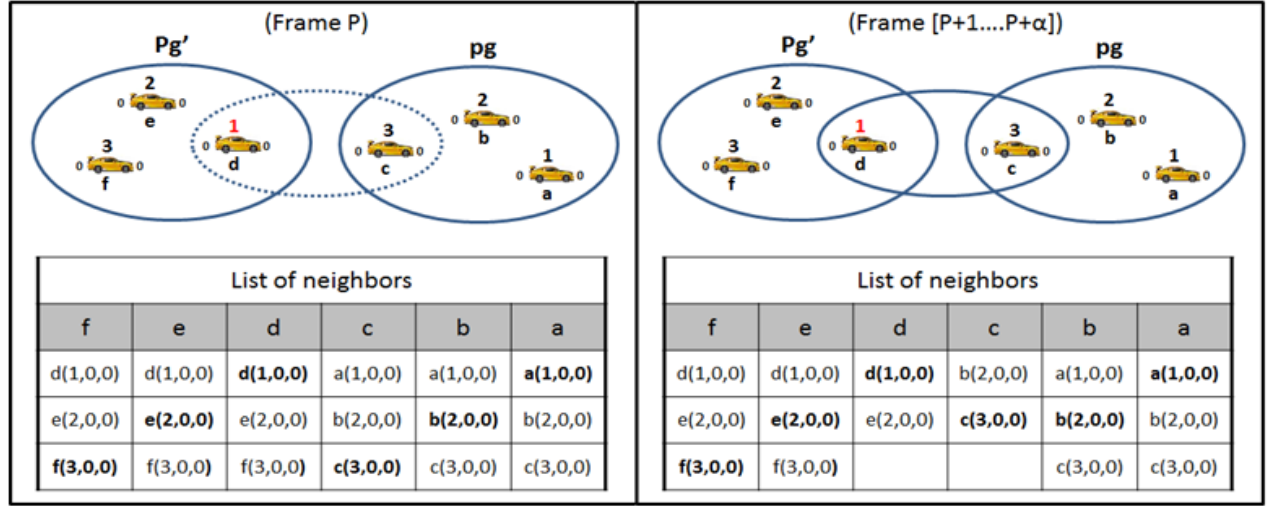


Figure 6.14: An example when the slot allocation process does not converge.

6.4 Simulation and results

6.4.1 Simulation

We have carried out extensive simulations to validate the performance of the CSTD MAC and compare it with IEEE802.11p/1609.4 MAC and performance analytic measuring the overhead generated, compare to ADHOC MAC and VeSOMAC. These simulations have been performed through the NS2 environment, where the considered road used to define a circular loop highway with 2 lanes unidirectional and bidirectional. The vehicles have the same and fixed communication range, the carrier sensing range is assumed to be the same as the communication range and the channel condition is assumed to be perfect for data transmission. The vehicles mobility is given by IMPORTANT mobility generator [79], where the speed of the vehicles is dependent on their previous speed and without lane changing.

The fact that the current study mainly concerned with the one-hop broadcast performance on the MAC layer, three metrics of interest are considered in this context which are:

1. The Dropped Beacon Rate (DBR): the number of collisions (which cause beacon drops) detected by the receiving antenna per second. This metric can reflect the throughput since the beacon always fits in single data without fragmentation,
2. The [Average Dropped Beacon Probability \(ADBP\)](#): the average number of dropped beacons divided by the number of the beacon sent during the simulation time.

3. Protocol Overhead (PO): the control information generated to achieve the slot allocation process.

As mentioned above, there are two types of transmission collisions; access collision and the merging collision, which happen among vehicles trying to acquire the same time slots, they can be detected according to the membership of the vehicles, causing the collision, to the same *pg* or *ipg* respectively.

Three scenarios have been implemented to study the performance of the MAC mechanisms against these transmission collisions types, the density of vehicles varies from medium to high value represented by 50 Veh/Km and 100 Veh/Km respectively, the mobility of vehicles are around three intervals, (0,0)km/h (used only to eliminate the merging collision and focusing only on the access collisions), (80-90) km/h and (80-120) Km/h when the merging collision is taking in account. The first scenario allows studying the Direct access collision, it includes vehicles moving in unidirectional highway with a length the same as the transmission range, which is supposed to be 300 m, to make the vehicle in the range of each other. The second scenario is a unidirectional highway of 1000 m long to study all the types of collisions through the variation of different mobility models. In the third scenario, the highway is bidirectional of a 1000 m long to study the influence of the inversed lanes direction on the merging collisions. Table 6.1 summarizes the simulation parameters.

Table 6.1: Simulation parameters.

Parameter	Value
Network simulator	NS2
Mobility generator	Important
Vehicle density	50, 100 veh
Vehicle mobility	(0-0) Km/h; (80-90) Km/h; (80-120)km/h
Road length	300 m, 1000 m
Lane	2
Communication range	300 m
Interference range	300 m
Slot/frame	500
Slot duration	1 ms
CW	3
Hello message size	300 byte
Hello message frequency	2 Hz
Simulation duration	50 seconds

6.4.2 Results

Figure 6.15 shows the rate of the direct access collisions (dropped beacons) within the first scenario, where the vehicles are in the same range of each other, for the MAC protocols under consideration. The CSTD MAC protocol achieves a low rate of collisions compared to IEEE 802.11p, since it assigns disjoint sets of time slots to vehicles. It can be observed that, as the system runs, the rate of collisions is progressively reduced until it goes to zero just in few seconds for the both density, the reason is that the CSTD MAC learns from successful transmission attempts in order to migrate to TDMA like operation, but with a high density the graph shows some ups and downs. As expected, the IEEE 802.11p protocol shows a considerably high rate of collisions for each second during all the simulation time, and this rate is doubled with the high density. These results are in support of what is shown in Figure 6.16, which presents the beacon collision probability of the studied MAC mechanism, where it can be observed that the IEEE 802.11p mechanism achieves approximately 80% higher probability of collision than the CSTD MAC under all densities.

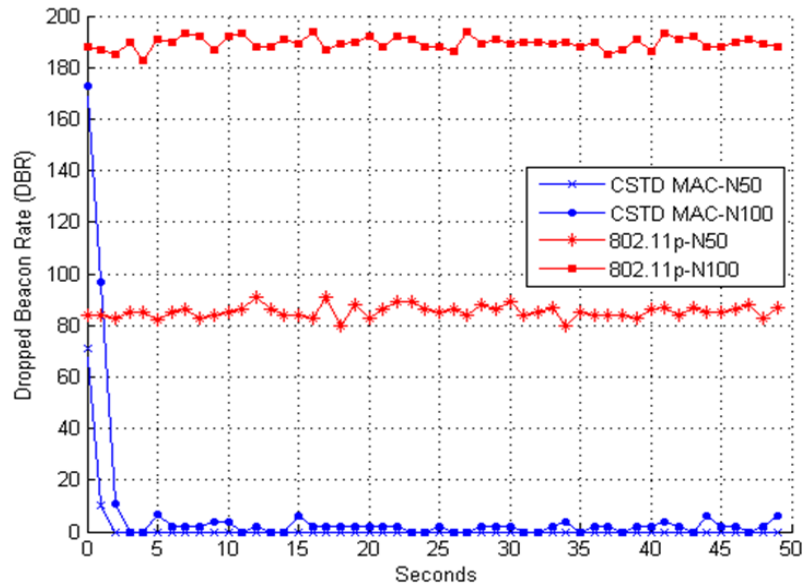


Figure 6.15: The rate of access collision in highway where all the vehicles are in the range of each other.

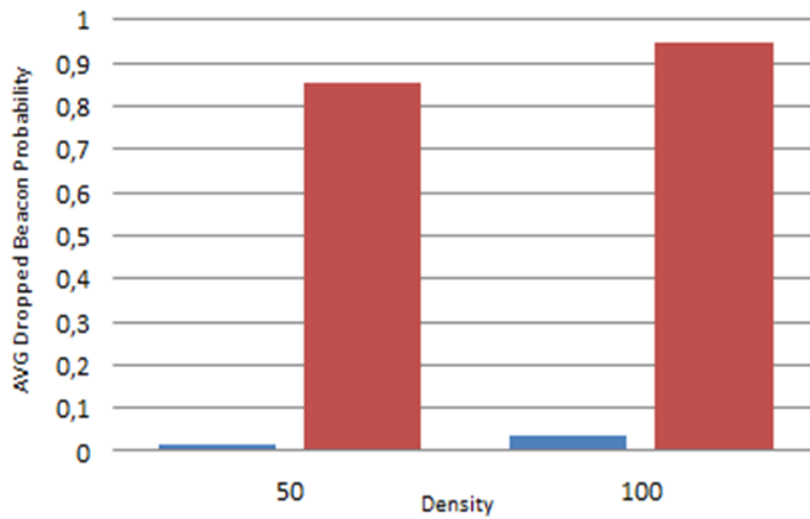


Figure 6.16: The probability of access collision in highway where all the vehicles are in the range of each other.

The rate of access and emerging collisions, which are caused by the distribution and the movement of vehicles, is shown in Figure 6.17 for the both MAC mechanisms. The first thing can be noticed is that the CSTD MAC solution shows better performance than the IEEE 802.11p mechanism under any density and velocity. As expected, Due to the learning ability the CSTD MAC the number of collision can decreases from the beginning but its cannot be eliminated totally, because this scenario is unlike the previous one, where all the vehicle are in the rage of

each other, in the current one the vehicles are distributed on the highway without movement, to make them being inside and hidden to the range of each other, the objective is to test the impact of hidden collisions. Based on the results of the first and the second scenario, it is clear that the collisions generated in the second scenario are caused by the hidden vehicles, so that the CSTD MAC protocol cannot eliminate them completely as well as the TDMA solutions, and the rate of collisions increases as the density increases. It is noted that, when the vehicles move, the CSTD MAC protocol shows a high rate of collision than the scenario where the vehicles are stationary, the reason is that, merging collisions happen due to the movement of vehicles. In the case of 802.11p protocol, a 50% increase in the number of collisions when the density of vehicles has been doubled, but it provides a similar results with and without mobility.

Figure 6.18 demonstrates the difference among the two protocols in term of collision probability, it is clear that IEEE 802.11p achieve approximately 50% higher probability of collision than CSTD MAC for all densities and mobilities. Note that, with the IEEE 802.11p for a medium density the collision probability increases very slightly with the increase of mobility, but with the high density it remains constant whatever the mobility taken, It can be explained by that fact that the merging collisions, which are caused by the mobility, have a negligible impact compared to the direct and the hidden collisions. For the CSTD MAC, the collision probabilities provided with mobile scenarios are approximately 50% higher compared to the stationary scenario, this under performing is a result of the excess of merging collisions where the protocol does not have any mechanism to avoid it.

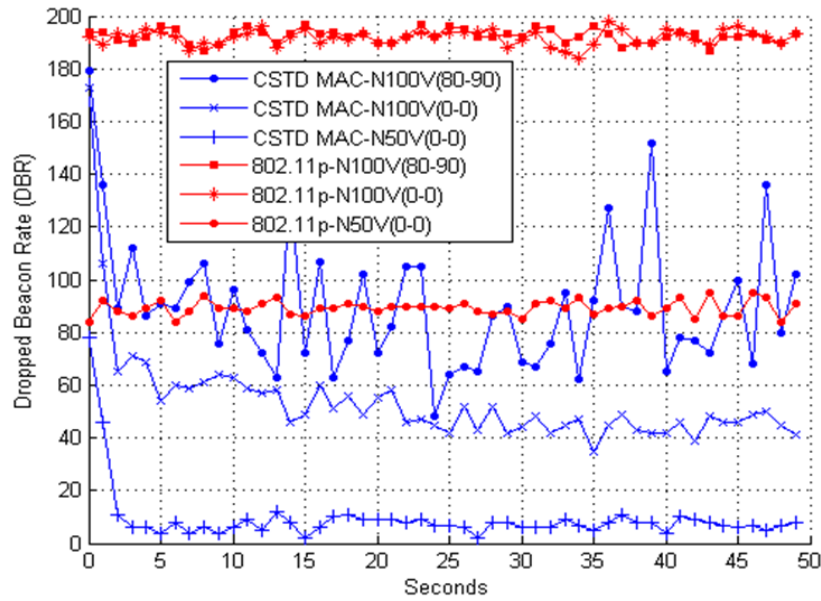


Figure 6.17: The rate of transmission collision in unidirectional highway of 1000 m.

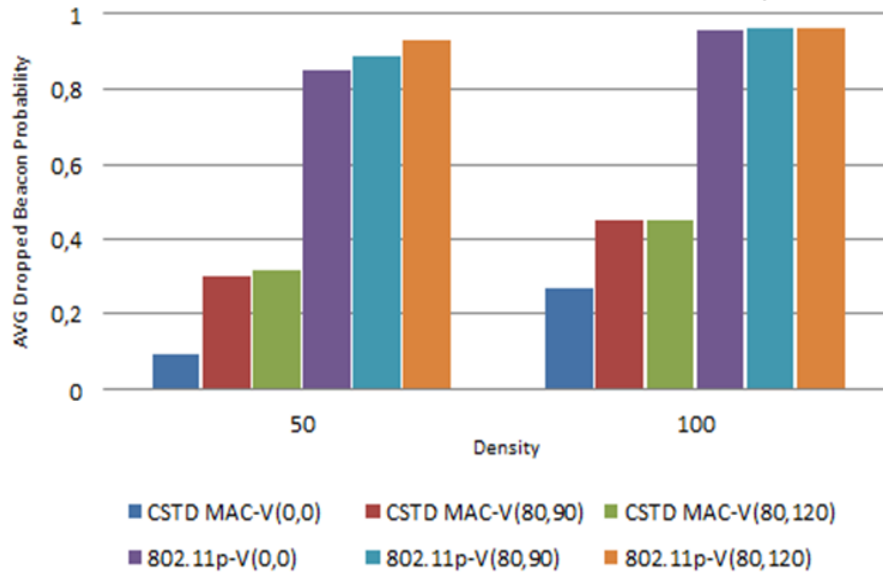


Figure 6.18: The probability of transmission collision in unidirectional highway of 1000 m.

Figure 6.19 shows the rate of merging collisions generated under two different scenarios, unidirectional, when the vehicles are moving in the same direction, and bidirectional, when they move in opposite direction; note that a medium density and mobility is used in the simulation and represented by 50 veh/Km and (80-90)Km/h respectively. Similar to the previews graphs presented in Figure 6.20, the IEEE 802.11p protocol provides a rate of collision which is higher than that of the CSTD MAC protocol, it achieves a close rate of merging collisions with two

scenarios. Contrariwise, the CSTD MAC protocol suffers from the merging collisions with bidirectional scenario. The results shown in Figure 6.20 prove the same observation; the collision probability achieved with the IEEE 802.11p cannot be affected by the movement direction of the vehicles under all densities, in the other hand, the CSTD MAC presents an increase of the collision probability when the vehicles move in opposite direction.

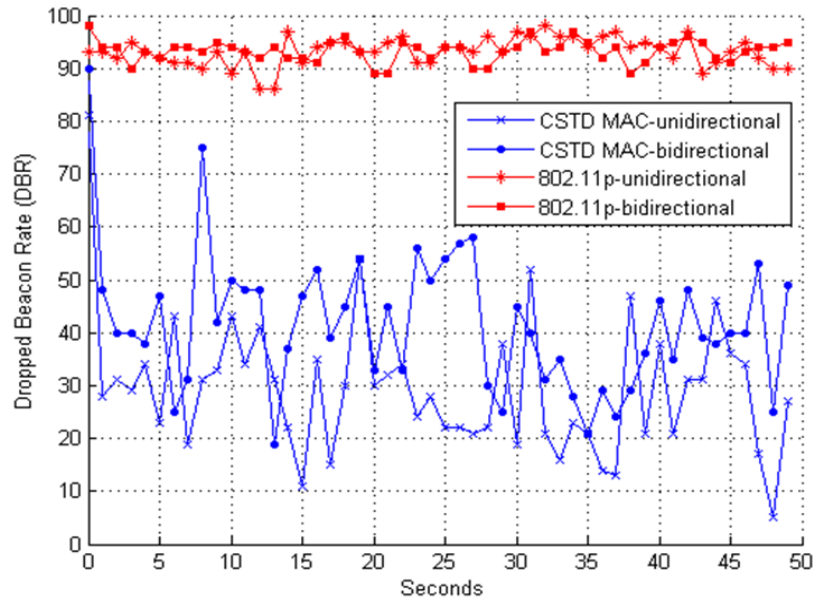


Figure 6.19: The rate of transmission collision in bidirectional highway of 1000 m under medium density and velocity.

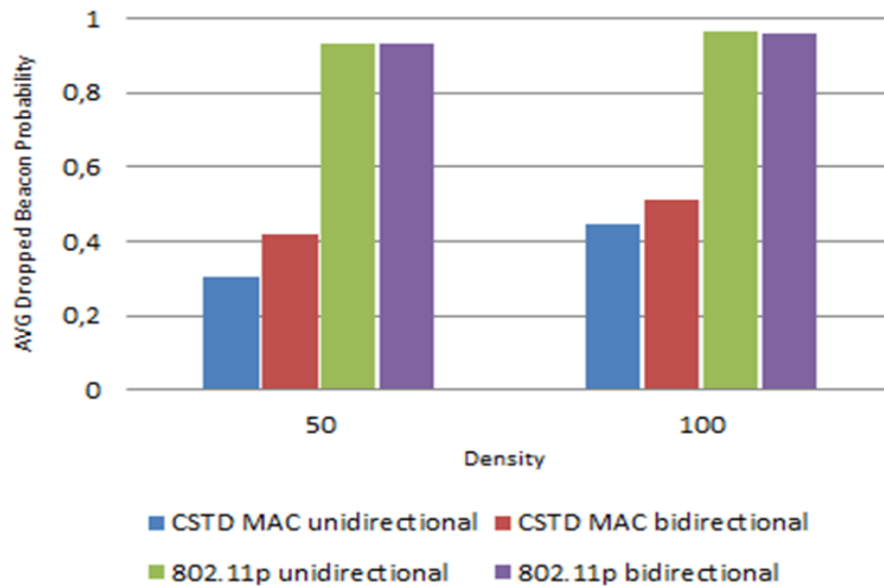


Figure 6.20: The probability of transmission collision in bidirectional highway of 1000 m under medium density and velocity.

Figure 6.21 illustrates the analytic performance of CSTD MAC protocol against the VeSOMAC and ADHOC protocols, in term of the overhead generated for the slot allocation under different vehicle densities, note that, the size of the frame is 100 slots. The CSTD MAC protocol is the lowest among all the MAC protocols, because it uses a short and fixed overhead for the slot allocation no matter the vehicle density in the road. VeSOMAC uses a dynamic bitmap table which increases according to the number of vehicles, and the ADHOC MAC presents the worst case by generating the highest overhead, equal to the size of the frame.

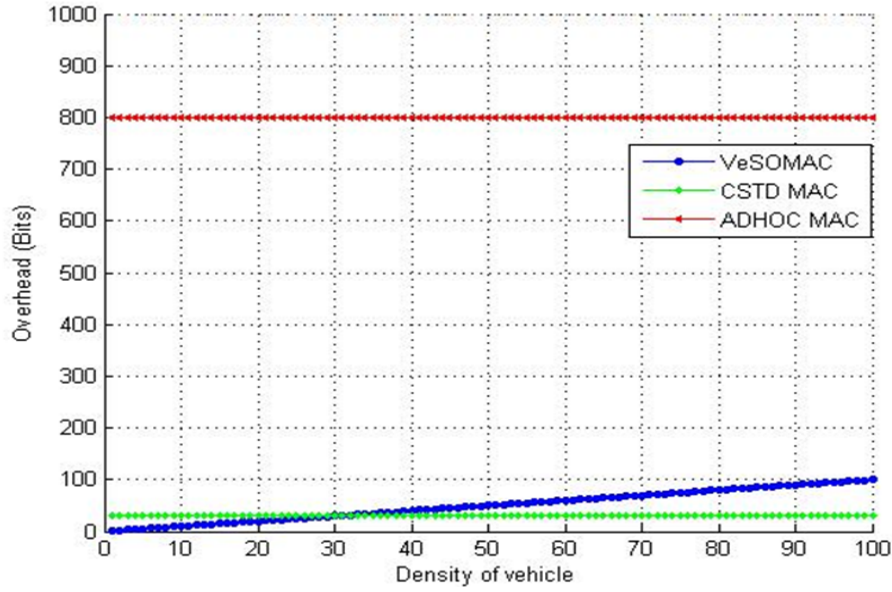


Figure 6.21: The overhead generated by the three medium access techniques: CSTD MAC, ADHOC-MAC and VeSOMAC.

6.5 Conclusion

This paper presents a new TDMA-like protocol for VANets. This new protocol ensures an efficient dynamic and distributed time slot allocation in highly dynamic wireless network environments. The main contribution in the presented solution consists of reducing the overall network overhead, while keeping the network performances high. The obtained simulation results show that CSTD MAC improves the network overhead by 90% compared to VeSOMAC and ADHOC MAC. Moreover, D-TDMA as a contention free MAC protocol, can reduce the transmission collisions and ensure better performances than CSMA of IEEE 802.11p. However, it suffers from the merging collisions when dynamicity of the network increases. Therefore, in fu-

ture works, it will be necessary to improve this by considering the merging collisions and take in account the frame saturation problem where the number of vehicles available in two intersected physical clusters is higher than the frame size.

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7.1 Summary

The main objective of this thesis is to support the QoS requirements of C-ITS safety applications, precisely the periodic one-hop broadcast service via an efficient MAC protocol. It addresses the reliability especially under high density scenarios, when transmissions must be carefully timed to maintain a high degree of awareness among the surrounding vehicles. To achieve this goal, the thesis has the following two contributions:

1. A state-of-the-art survey is established for the medium access mechanisms which are categorized into two main classes. The first one is the asynchronous CSMA-based MACs which are characterized by their simplicity, distributed nature, freedom from central coordinator, effectiveness to deal with mobility and topology changes without any synchronization among vehicles. The second class is the Synchronous time-slotted-based MACs which have the potential to solve the main issues of CSMA/CA known as the hidden terminals problem. However, the main challenge for the synchronous time-slotted-based MACs is the slot reservation which needs a frequent and heavy signaling. Combining the benefits and avoiding the limits of the two MAC classes are considered carefully when developing the proposal protocol.

2. A reliable one-hop broadcast MAC protocol is proposed which is called CSSA MAC (Carrier Sense for Slotted-ALOHA random multiple access MAC). The proposal describes how the periodic messages (beacons) are served just by combining the simple mechanism of the two MAC protocol: CSMA and Slotted-ALOHA. It can be seamlessly integrated in IEEE 1609.4 on top of the IEEE 802.11p standard. It consists of two parts: 1) spreading the vehicle's beacons: at the beginning of each CCH interval, the beacons' transmission time the contending vehicles are spread over a SW from the CCH interval. Therefore, CCH period is virtually slotted the same way as S-ALOHA MAC method where the virtual slots represent the possible STT of the beacons (a STT is randomly allocated for each beacon). Such solution can be enabled through a minor modification to the IEEE 1609.4 standard; and 2) medium access: when the STT is reached, a vehicle has a chance to access the channel, and attempts to transmit using the conventional IEEE 802.11p's CSMA/CA. An analytical analysis is made in order to calculate the optimal SW size according to the number of contending vehicles. By using a mathematical model, it was possible to predict the ratio of contention, the probability of successful transmission and collisions, and the wasted time between the first and the last successful transmission. To confirm and verify the effectiveness of theoretical results, a simulation study is performed using NS2 to evaluate the performance of the proposal CSSA MAC in comparison with the IEEE 802.11p standard and some famous MAC protocols like SDMA which is considered as one of the best contention-free MAC. Simulation results show that CSSA MAC provides a smaller rate of transmission collisions compared to the IEEE 802.11p standard and lightly higher than that of the SDMA MAC, which results in a significantly higher performance on the CCH. The outperforming of the proposal is that it can provide a good performance proximate to the SDMA MAC mechanism without using the slot-space map calendar and the GPS.

Since that the vehicular network have a different network situations and application requirements, Combining the mechanisms of CSMA-like MAC and TDMA-like MAC can be seen as a complete framework for congestion control for vehicular communications for safety applications. The research done in this thesis presents the CSSA MAC as a promising protocol for MAC in VANETs and a suitable replacement of the IEEE 802.11p standard, which have significant

limitations in supporting VANET safety applications. However, further improvements for the CSSA MAC are needed in the future.

7.2 Future work

Some future perspectives should be taken into account in order to improve the current work and reach the thesis vision. They can be listed as follows:

1. The back-off mechanism used in the CSSA MAC does not take into consideration the number of beacons affected to a given STT after the spreading stage. Because of the random affectation and the use of a constant contention window, it may happen that some STTs will receive a lot of beacons and have more contention than the others. Predicting the number of beacons in each STT is considered as an occupancy problem which needs a mathematical analysis to estimate the optimal size of CW.
2. It is important to study the performance of CSSA MAC protocol under a high channel load which is represented by a high number of neighbor's vehicles within a common communication range and a high generated beacon rate.
3. This work is mainly focused on only safety beaconing of the CAM/BSM message. However, the efficiency of the event-driven DENM message through multi-hop dissemination, which is transmitted when an important event is detected, is also essential for the success of road safety applications. The MAC protocol must include mechanisms for the co-existence of the two kinds of messages where the highest priority is assigned to the DENM.
4. The CSSA MAC should be extended to calculate dynamically the local density within two hops of transmission range and to be evaluated by simulating its performance in a real vehicular scenario.
5. The random selection of STT is suitable for a high dynamic topology. However the STT reservation strategy, as used in TDMA MAC mechanism, is beneficial solution under stable topology. In previous work [20], we have proposed a TDMA scheme which uses an in-band signalization with small overhead to allocate time slots to the contending vehicles in a distributive manner. Using this mechanism is promising approach to enhance the

performance of CSSA MAC and improve the adaptability of the protocol under both dynamic and stable topology.

6. The Support of beaconing and event-driven safety messages via the Long Term Evolution Advanced (LTE-A) mobile communications standard is a promising research topic. As an extended work, many issue need to be investigated to determine how the LTE-A, which is represented by the 5G technology, can co-exist with the direct communication in VANET.

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