UNIVERSIDAD POLITÉCNICA DE VALENCIA

DEPARTMENT OF COMPUTER ENGINEERING

Design and Evaluation of Efficient Medium Access Control Solutions for Vehicular Environments

Thesis submitted in partial fulfillment of the requirements
for the degree of Doctor of Philosophy in Computer Science

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To my wife, Mahshid, my parents, and my sister, Zahra.

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Ali Balador
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Abstract

In recent years, advances in wireless technologies and improved sensing and computational capabilities have led to a gradual transition towards Intelligent Transportation Systems (ITS) and related applications. These applications aim at improving road safety, provide smart navigation, and eco-friendly driving. Vehicular Ad hoc Networks (VANETs) provide a communication structure for ITS by equipping cars with advanced sensors and communication devices that enable a direct exchange of information between vehicles. Different types of ITS applications rely on two types of messages: periodic beacons and event-driven messages. Beacons include information such as geographical location, speed, and acceleration, and they are only disseminated to a close neighborhood. Differently from beacons, event-driven messages are only generated when a critical event of general interest occurs, and it is spread within a specific target area for the duration of the event.

The reliability of information exchange is one of the main issues for vehicular communications since the safety of people on the road is directly related to the effectiveness of these transmissions. A Medium Access Control (MAC) protocol must guarantee reliable beacon broadcasting within deadline bounds to all vehicles in the neighbourhood, thereby providing them timely notifications about unsafe driving conditions or other hazardous events. Moreover, infotainment and comfort applications require reliable unicast transmissions that must be taken into account. However, high node mobility, highly dynamic topology, and lack of a central control unit, are issues that make the design of a reliable MAC protocol for vehicular environments a very difficult and challenging task, especially when efficient broadcasting strategies are required.

The IEEE 802.11p MAC protocol, an approved amendment to the IEEE 802.11 standard, is a random access protocol that is unable to provide guaranteed delay bounds with sufficient reliability in vehicular scenarios, especially under high channel usage. This problem is particularly serious when implementing (semi-) automated driving applications such as platooning, where inter-vehicle spacing is drastically reduced, and the control loop that manages and maintains the platoon requires frequent, timely and reliable exchange of status information (beacons).

In this thesis novel protocols compatible with the IEEE 802.11 and 802.11p standards are proposed in order to optimally adjust the contention window size for unicast applications in Mobile Ad hoc Networks (MANETs) and VANETs. Experimental tests comparing our proposals to existing solutions show that the former are able to improve the packet delivery ratio and the average end-to-end

delay for unicast applications.

Concerning efficient message diffusion (broadcast) in VANET environments, we proposed token-based MAC solutions to improve the performance achieved by existing 802.11p driving safety applications in different vehicular environments, including highway, urban, and platooning scenarios. Experimental results show that the proposed solutions clearly outperform 802.11p when delay-bounded beacons and event notifications must be delivered.

Resumen

Recientemente, los avances en las tecnologías inalámbricas y las mejoras en términos de capacidades de sensorización y computación de los dispositivos electrónicos, han dado lugar a una transición gradual hacia servicios y aplicaciones de los Sistemas Inteligentes de Transporte (ITS).

Estas aplicaciones tienen como objetivo mejorar la seguridad vial, proporcionar una navegación inteligente, y promover la conducción eco-eficiente. Las redes vehiculares ad hoc (VANETs) proporcionan una infraestructura de comunicaciones para ITS al equipar los coches con sensores avanzados y dispositivos de comunicación que permiten el intercambio directo de información entre vehículos.

Los diferentes tipos de aplicaciones ITS se basan en dos tipos de mensajes: mensajes periódicos conocidos como beacons y mensajes asociados a eventos. Los mensajes periódicos incluyen información relativa a la ubicación geográfica, la velocidad y la aceleración, entre otros, y sólo son distribuidos entre los vehículos vecinos. A diferencia de estos beacons, los mensajes asociados a eventos sólo se generan cuando se produce un evento crítico de interés general, el cual se propaga dentro del área de interés de dicho evento y mientras éste siga activo.

La fiabilidad del intercambio de información es uno de los principales problemas para las comunicaciones vehiculares, debido principalmente a que las aplicaciones de seguridad dependen directamente de la eficacia de estas transmisiones.

Un protocolo de Control de Acceso al Medio (MAC) debe garantizar la difusión fiable de información a todos los vehículos vecinos dentro de unos límites máximos de retardo, proporcionándoles las notificaciones oportunas respecto a condiciones de conducción inseguras y otros eventos peligrosos.

Por otra parte, las aplicaciones de información y entretenimiento, así como las aplicaciones orientadas al confort, también requieren transmisiones fiables extremo-a-extremo. Sin embargo, la alta movilidad de los vehículos, la variabilidad de la topología, así como la falta de una unidad central de control, son factores que hacen que el diseño de un protocolo MAC fiable para entornos vehiculares sea una tarea especialmente compleja, especialmente cuando son necesarias estrategias de difusión eficientes.

El protocolo MAC IEEE 802.11p, una modificación ya aprobada al estándar IEEE 802.11 original para entornos de comunicación vehiculares, es un protocolo de acceso que no es capaz de garantizar unos límites de retardo con la fiabilidad necesaria para estos entornos, especialmente en escenarios de alta utilización del canal inalámbrico. Este problema es particularmente importante a la hora de implementar aplicaciones de conducción (semi-)automática, como el caso de grupos de vehículos donde la separación entre vehículos se reduce drásticamente, y el sistema de control que gestiona y mantiene el grupo requiere de un intercambio frecuente de información fiable y acotado en retardo.

En esta tesis se proponen nuevos protocolos MAC compatibles con los estándares IEEE 802.11 y 802.11p basados en el ajuste del tamaño de la ventana de contención para aplicaciones unicast en rede MANETs y VANETs. Los resultados experimentales obtenidos comparando nuestras propuestas con las soluciones existentes muestran que los protocolos propuestos son capaces de mejorar la tasa de entrega de paquetes y el retardo medio extremo-a-extremo para aplicaciones unicast.

En lo que respecta a la difusión eficiente de mensajes broadcast en entornos VANET, se han propuesto soluciones MAC basadas en el uso de tokens que mejoran las prestaciones de aplicaciones de conducción segura basadas en el estándar 802.11p, tanto en autopistas, zonas urbanas, y escenarios con grupos de vehículos. Los resultados experimentales muestran que las soluciones propuestas superan claramente al protocolo 802.11p cuando es necesario entregar mensajes y notificaciones de eventos con restricciones de latencia.

Resum

Recentment, els avan en les tecnologies sense fils i les millores en termes de capacitats de sensorització i computació dels dispositius electrònics, han donat lloc a una transició gradual cap a serveis i aplicacions dels sistemes intelligents de transport (ITS).

Aquestes aplicacions tenen com a objectiu millorar la seguretat vial, proporcionar una navegació intelligent, i promoure la conducció ecoeficient. Les xarxes vehiculars ad hoc (VANET) proporcionen una infraestructura de comunicacions per a ITS, ja que equipen els cotxes amb sensors avançats i dispositius de comunicació que permeten l'intercanvi directe d'informació entre vehicles.

Els diversos tipus d'aplicacions ITS es basen en dos classes de missatges: missatges periòdics coneguts com a beacons i missatges associats a esdeveniments. Els missatges periòdics inclouen informació relativa a la ubicació geogràfica, la velocitat i l'acceleració, entre uns altres, i només són distribuïts entre els vehicles veïns. A diferència d'aquests beacons, els missatges associats a esdeveniments només es generen quan es produeix un esdeveniment crític d'interès general, el qual es propaga dins de l àrea d'interès d'aquest esdeveniment i mentre aquest seguisca actiu.

La fiabilitat de l'intercanvi d'informació és un dels principals problemes per a les comunicacions vehicular, principalment perquè les aplicacions de seguretat depenen directament de l'eficàcia d'aquestes transmissions.

Un protocol de control d'accés al medi (MAC) ha de garantir la difusió fiable d'informació a tots els vehicles veïns dins d'uns límits màxims de retard, i proporcionar-los les notificacions oportunes respecte a condicions de conducció insegures i altres esdeveniments perillosos.

D'altra banda, les aplicacions d'informació i entreteniment, com també les aplicacions orientades al confort, també requereixen transmissions fiables extrem-a-extrem. No obstant això, l'alta mobilitat dels vehicles, la variabilitat de la topologia, i la falta d'una unitat central de control, són factors que fan que el disseny d'un protocol MAC fiable per a entorns vehiculars siga una tasca especialment complexa, especialment quan són necessàries estratègies de difusió eficients.

El protocol MAC IEEE 802.11p, una modificació ja aprovada a l'estàndard IEEE 802.11 original per a entorns de comunicació vehiculars, és un protocol d'accés que no és capa garantir uns límits de retard amb la fiabilitat necessària per a aquests entorns, especialment en escenaris d'alta utilització del canal sense fil. Aquest problema és particularment important a l'hora d'implementar aplicacions de conducció (semi)automàtica, com el cas de grups de vehicles en què la separació entre vehicles es redueix dràsticament, i el sistema de control que gestiona i manté el grup requereix un intercanvi freqüent d'informació fiable i delimitat en retard.

En aquesta tesi es proposen nous protocols MAC compatibles amb els estàndards IEEE 802.11 i 802.11p basats en l'ajust de les dimensions de la finestra de contenció per a aplicacions unicast en xarxes MANET i VANET. Els resultats experimentals obtinguts comparant les nostres propostes amb les solucions existents mostren que els protocols proposats són capa de millorar la taxa de lliurament de paquets i el retard mitjà extrem-a-extrem per a aplicacions unicast.

Pel que fa a la difusió eficient de missatges broadcast en entorns VANET, s'han proposat solucions MAC basades en l'ús de tokens que milloren les prestacions d'aplicacions de conducció segura basades en l'estàndard 802.11p, tant en autopistes, zones urbanes, i escenaris amb grups de vehicles. Els resultats experimentals mostren que les solucions proposades superen clarament el protocol 802.11p quan cal lliurar missatges i notificacions d'esdeveniments amb restriccions de latència.

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Chapter 1

Introduction

1.1 Motivation

Energy and safety have emerged as two critical issues for the automotive industry. A high number of people die in road accidents worldwide every year, which causes economic losses to victims, their families, and to nations, such as the cost of treatments, reduced/lost productivity for those killed or disabled by their injuries, as well as for families to take care of the injured. As a result, safety issues have received much attention for the future direction of vehicles and Intelligent Transportation Systems (ITS) [SDT96]. Also, ITS can lead to a significant decrease in the energy consumption and global carbon emissions, particularly for platoons of vehicles.

While different passive safety features, such as bumpers, crumple zones, airbags, and seatbelts have been introduced, fatality rates have been fairly stable over the last decade, as shown in Figure 1.1. Advances in wireless technologies, along with improved sensing and computational capabilities, pave the ground for another type of safety systems, usually referred to as active traffic safety systems. Passive safety systems are purely about minimizing injuries and damages during or shortly after a crash. In contrast, active traffic safety systems, or more specifically cooperative traffic safety systems, attempt to avoid these accidents by preventing dangerous situations by accounting for information obtained from the vehicle's surroundings, including traffic and road conditions. To provide a cooperative traffic safety system, all vehicles have to exchange their in-vehicle sensors information with other existing vehicles in their close proximity or near-by Road Side Units (RSUs). These systems have a great potential by allowing to warn the driver and give her/him an opportunity to react properly, or by providing an autonomous control system the ability to automatically react to the situation in a fraction of second. Example of such active safety applications are collision warning at intersections, overtaking warning, and lane change warning [TCSZ11].

Academic, industrial, and standardization organizations have started a collaboration in order to choose a dedicated frequency band for ITS, and also for designing, evaluating and standardizing new protocols operating in this frequency

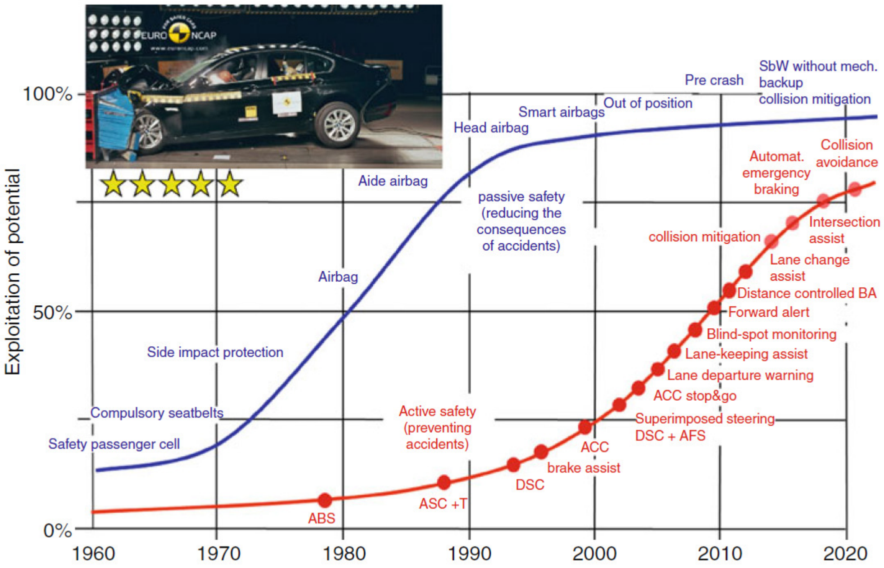


Figure 1.1: Exploitation of potential of active and safety systems [KDK12].

band. Although a lot of effort has been done in this area, it is still in its infancy, and there is room for further investigation to propose new communication protocols compatible with the specific requirements of vehicular networks. This thesis contributes to the development of cooperative driving systems by proposing new Medium Access Control (MAC) protocols specially developed for safety applications in vehicular scenarios.

1.2 Challenges and Research Questions

The main challenges we are facing in the implementation of cooperative driving applications can be summarized in the following points:

- **Highly dynamic topology**
  A vehicular network is highly dynamic because of the high relative speed of the vehicles and the frequent changes in the environment. For example, vehicles have high relative speeds of 50 km/h in urban scenarios, while in highway scenarios, speeds typically increase beyond 100 km/h. Therefore, for Vehicle-to-Vehicle (V2V) communications, the links between two vehicles experience frequent disconnections. For Vehicle-to-RSU communications, vehicles passing near a stationary RSU will be located within its radio range for a short period of time due to their high speed. In addition, the time required to join an access point and hand over between two access points will add to the challenges. This also introduces difficulties for forwarding packets because the vehicle chosen as information relay might not maintain its location long enough, moving before receiving the information. For an

application's point of view, a high levels of vehicular mobility may lead to a situation where information is outdated or received very late, failing to provide enough time for the driver or the system to react to a hazardous situation.

- **Lack of a centralized management and coordination entity**
  The fair and efficient management of the available bandwidth of wireless networks in a totally decentralized network is a very hard task. Moreover, the tight delay requirements of vehicular safety applications requires MAC protocols to guarantee the maximum channel access delay for all nodes.

- **Inherent characteristics of the radio environments**
  Two commonly used scenarios for vehicular environments include highway and urban scenarios. In a highway, the signal strength can be attenuated by the vehicles located between the transmitter and the receiver, so its detection at the receiver side may be difficult or impossible. In an urban environment, the communication is even more complex due to the presence of vehicles, buildings, trees, and other objects, acting as obstacles to the signal propagation. Such obstacles cause shadowing, multi-path, and fading effects.

- **Limited resources**
  Efficient management of the radio channel is always a major challenge for different wireless communication technologies since the spectrum resources are limited. All vehicles have to access the same channel in order to transmit their packets. Therefore, the probability of two or more nodes simultaneously accessing the channel is very high. In vehicular scenarios, and particularly for busy multi-lane highways, this is even more challenging because the number of communicating vehicles can easily reach several hundred nodes. The main task of a MAC protocol is to shared the available bandwidth between all network members in a scalable, reliable, efficient and fair way, while attempting to maintain channel access delay as low as possible.

- **Traditional performance metrics are not directly applicable**
  Choosing optimal performance metrics is not an easy task, and it must be performed considering the proposed protocol and the simulation scenario to accurately show the real performance of the proposed protocols. For safety applications, reliability is more important than transmission rates. Therefore, typical performance metrics, such as throughput or delay, which are suitable for comfort or infotainment applications, become less important. All traffic safety applications are deadline dependent, and so metrics must be chosen wisely to capture both the delay beyond the deadline and the probability of losing messages due to failures in the communication link.

For the scope of this thesis, these challenges can be summarized in the following research questions:

1. Is the random access MAC method used in the IEEE 802.11p standard [IEE12] suitable for different transmission modes, including unicast and

broadcast, as required to fulfil the requirements of different types of cooperative driving applications? And what is the impact of the different enhancements to the standard proposed on this thesis on the overall performance?

2. How can the channel be managed efficiently considering the vehicular environment characteristics and cooperative driving applications requirements on timing and reliability?

3. What is the impact of our proposals to the standard for delay sensitive automated driving applications, e.g., platooning?

1.3 Objectives

The global objective of this thesis is to propose efficient MAC protocols for different types of ad hoc networks, especially focusing on Vehicular Ad hoc NETworks (VANETs). In order to achieve the main goal of this thesis, a set of objectives have been proposed as follows:

- A review of existing medium access techniques must be performed in order to evaluate previously proposed solutions, including both particular proposals and standards for different ad hoc networks.

- Efficient MAC protocols must be developed for the different types of ad hoc networks considering their specific characteristics.

- Apart from general scenarios, different cooperative driving applications require different levels of timing and reliability, which must be considered in order to propose new solutions.

- Moreover, an analytical analysis should be presented to support our simulation evaluations.

- For evaluation purposes, different performance metrics should be studied and optimal metrics should be chosen to compare existing solutions against our own.

- Simulation evaluations must be done in order to validate the analytic models, and to perform a comparison between the proposed protocols and other existing standards and solutions. In particular, it should be able to simulate different MAC protocols and environments, including highway, urban, and platooning scenarios. For this reason, a simulation framework must be provided including an accurate wireless network simulator (OMNeT++ or NS-2) [Var99, FV11], implementations of the target protocol architecture and channel model, third-parties add-ons for vehicular traffic generation such as the SUMO traffic generator [BK11], and extensions to guarantee a stable number of vehicles in the experiments.

1.4 Structure of the Thesis

This thesis is organized in five chapters as follows: in chapter 2 we make a background introduction to both Mobile Ad hoc NETwork (MANET) and VANET environments. We introduce some basic concepts of these networks, and we then proceed to explain the basics of the IEEE 802.11 standard [ANS03], and its amendment for vehicular ad hoc networks, IEEE 802.11p standard. Also, we review the work related to the design of MAC protocols for each of these networks.

In chapter 3 we propose different IEEE 802.11-based MAC protocols for MANETs and VANETs by focusing on unicast communication. Moreover, this chapter includes all simulation settings and evaluations for each proposed MAC protocol that was presented before in this chapter.

Chapter 4 explains in detail our token-based MAC protocol. We propose a MAC protocol using the token passing idea in order to handle channel access requests. Several common scenarios, including highway and urban scenarios are used for evaluating the performance of the solution proposed in this chapter.

In chapter 5 we focus on an specific automated driving application usually known as platooning which requires a timely and reliable MAC solution. Moreover, both analytical analysis and simulation evaluations are used in order to show the effectiveness of the proposed enhancements for platooning applications compared to the standard.

Finally, the conclusions of this thesis are presented in chapter 6. Also, a list of the publications related to the thesis, as well as the open research issues that can be derived from the work accomplished in this thesis, are presented.

Chapter 2

Background

2.1 Mobile Ad hoc NETwork (MANET)

This chapter provides background information about mobile and vehicular ad hoc networks. We first discuss some basic concepts associated to these networks, and then proceed by focusing on MAC layer standards and previously proposed MAC solutions in order to highlight important issues and challenges when designing new protocols.

2.1.1 Overview

MANETs [CG14] represent complex distributed systems where wireless mobile nodes can freely and dynamically self-organize to create temporary network topologies, thereby providing network services in areas with no pre-existing communication infrastructure. Traditionally, the ad hoc paradigm has been used for military applications, but with the emergence of new technologies such as Bluetooth [STYW04] and IEEE 802.11, commercial MANET deployments outside the military domain have shown a significant growth. In a MANET, each node is able to communicate directly with any other node in its transmission range. Communication between nodes that are not located in each others' transmission range is performed via multi-hop relaying. For this reason, every ad hoc node must act as a router and forward messages from other nodes. Figure 2.1 illustrates the multi-hop routing concept in MANETs.

The main advantages of ad hoc networks are flexibility, low cost, and robustness. Ad hoc networks can be easily set up, even in military situations, and they can tolerate natural disasters. These issues make ad hoc networks well suited for a variety of applications ranging from ad hoc video/audio conferencing through wireless sensor networks, wearable computers, networked robots, emergency rescue communication networks, defense tactical communications, context-aware environments, and so on [CG14]. In general, mobile ad hoc networks can be used in all those situations where there is little or no communications infrastructure, or when the existing infrastructure is expensive or inconvenient to use.

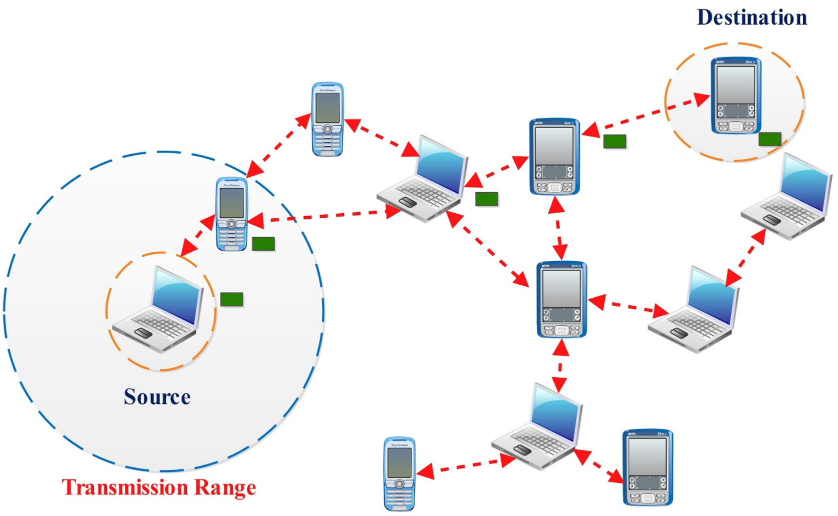


Figure 2.1: Example of multi-hop routing in MANETs.

Traditional problems of wireless networks also prevail in MANETs. At the physical layer the main challenges are: low transmission rate, high bit error rates, limited range, and significant variations in channel conditions. At the MAC layer, besides collision detection, hidden and exposed terminal problems must be taken into account. In addition, their multi-hop nature and the lack of fixed infrastructure creates new challenges in MANETs. Nodes change their locations frequently and unpredictably, resulting in frequent topology changes, network partitioning, and possibly packet losses. Therefore, new routing and transport protocols have to be designed to cope with the new challenges.

In addition, many other issues such as limited resources, have to be addressed when designing a mobile ad hoc network. Since mobile nodes rely on constrained energy sources, e.g., batteries, for their tasks, services and applications offered by a mobile node are limited. Compare to wireless networks, energy is more challenging since each node acts as both an end system and a router to forward packets from other nodes. Also, mobile nodes may be equipped with one or more radio interfaces, which leads to more energy consumption. Network scalability is another important issue due to the large number of mobile nodes that must be supported by mobile ad hoc network applications. Security is much more difficult to maintain in MANETs compared to traditional wireless networks since nodes can freely join and leave the network and, therefore, there is no clear line of defense. Also, malicious and selfish behaviors emerge as new challenges that are hard to detect in MANETs due to their decentralized nature.

2.1.2 MAC Layer Issues

The efficiency of wireless channel access is a critical issue because the bandwidth of a wireless network is limited, and the channel is shared among network nodes (i.e., each node competes with other nodes having packets to transmit). Besides, a wireless channel is error prone, and thus packets may be corrupted in the channel due to transmission errors such as channel noise, path loss, fading, and interference. In addition to the aforementioned issues, the following two important problems must be tackled in wireless networks:

1. **The "hidden node" problem**: As illustrated in Figure 2.2, node B is within the radio transmission range of nodes A and C, but nodes A and C are not in each other's range. This causes node A to be unaware that node B is currently busy receiving from node C, and therefore it starts a new transmission, causing a collision. This is referred to as the "hidden node" problem.

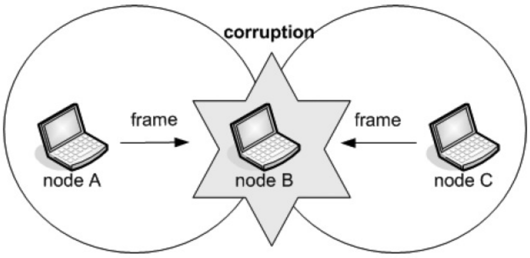


Figure 2.2: The hidden node problem.

2. **The "exposed node" problem**: This problem occurs when a node is preventing other nodes from sending packets due to a neighboring transmitter, as shown in Figure 2.3. For example, node C wants to transmit to node D but mistakenly thinks that this will interfere with B's transmission to A, so C refrains from transmitting. The "exposed node" problem leads to loss of efficiency.

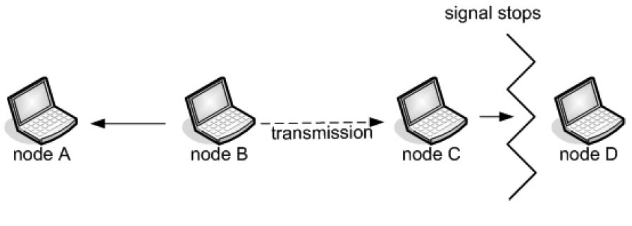


Figure 2.3: The exposed node problem.

2.1.3 IEEE 802.11 MAC

Although initially proposed for Wireless LAN environments, the IEEE 802.11 standard has expanded in order to fulfill the communication requirements of different environments. IEEE 802.11-based MAC protocols rely on the Carrier Sense Multiple Access with Collision Avoidance (CSMA/CA) mechanism, so that each node listens to the channel before transmission in order to prevent collisions. Since they cannot guarantee a collision-free MAC, two main mechanisms are proposed to handle medium access collisions among nodes, while also avoiding the hidden node problem. First, the Request-to-Send (RTS)/Clear-to-Send (CTS) mechanism is proposed in order to reserve the medium by sending small packets before transmitting large data packets, basically to avoid the hidden node problem. Each node that has a data packet for transmission sends a RTS packet and waits in order to receive a CTS packet. Receiving a CTS packet means that the receiver is ready to receive a data packet.The transmitter must wait for a predefined period of time after receiving the CTS packet, and then it begins to send its own data packets. However, due to the high overhead involved when using this mechanism, it is inactive by default. Second, each node must select a random time (called backoff) before sending each packet to avoid packet collisions. In addition to physical carrier sensing, IEEE 802.11 supports the virtual one. This is implemented in the form of a Network Allocation Vector (NAV), which is maintained by every node. The NAV indicates the amount of time that must elapse until the current transmission is complete, and the medium can be checked again for idle status. IEEE 802.11 proposes three different Inter Frame Space (IFS) time intervals, such as SIFS, PIFS, and DIFS, in order to prioritize access to the wireless channel:

- Short IFS (SIFS) time intervals have the highest access priority to the channel, and are used for control packets.
- Point coordination function IFS (PIFS) time intervals are used in the IEEE 802.11 Point Coordination Function (PCF) mode for the access point to gain control of the channel.
- Distributed coordination function IFS (DIFS) time intervals are used for the transmission of data packets under normal circumstances.

Figure 2.4 shows the different IFS time intervals.

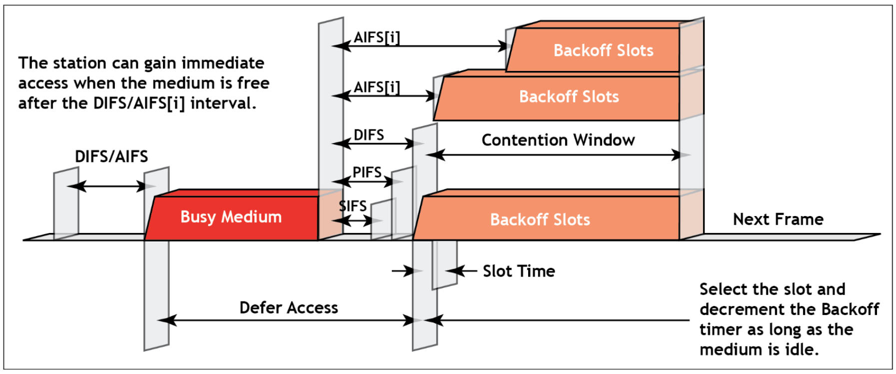


Figure 2.4: Inter Frame Space (IFS) time intervals.

When a new data packet is waiting in the buffer for transmission, the node is allowed to transmit the packet if it finds the channel free after waiting for a time equal to DIFS. Otherwise, if the channel is found busy after this period, it chooses a backoff value and must wait before attempting to transmit again. The next time the channel is found idle, the node must wait for a time equal to DIFS, plus a backoff time before transmission. The Binary Exponential Backoff (BEB) algorithm uniformly selects the backoff time from the interval (0,CW). The IEEE 802.11 standard initializes the Contention Window (CW) to the minimum predefined value, CW_{min}, and doubles it upon transmission failures up to the maximum predefined value, CW_{max}. Also, the CW is reset to CW_{min} by a successful transmission. The backoff timer is decreased by one for each idle slot and paused if the channel is sensed busy. The backoff timer is resumed when the channel again remains idle for a period longer than DIFS. IEEE 802.11 uses a positive Acknowledgement (ACK) to confirm the correctness of the current transmission to the transmitter. Such mechanism is mandatory since wireless interfaces cannot transmit and listen to the channel simultaneously. Notice that its own signal is too strong, masking any other incoming signals, and so collision detection becomes very difficult. In addition, collision detection at the transmitter side does not allow inferring about collisions at the receiver side. Therefore, if the transmitter cannot receive a correct ACK packet, it considers that a collision has occurred, and the current data packet must be retransmitted (up to a predefined number of times). After receiving a correct data packet, the receiver waits for a SIFS time, and then sends an ACK to the transmitter. Figure 2.5, shows the routines adopted by the IEEE 802.11 standard in terms of MAC protocol mechanisms.

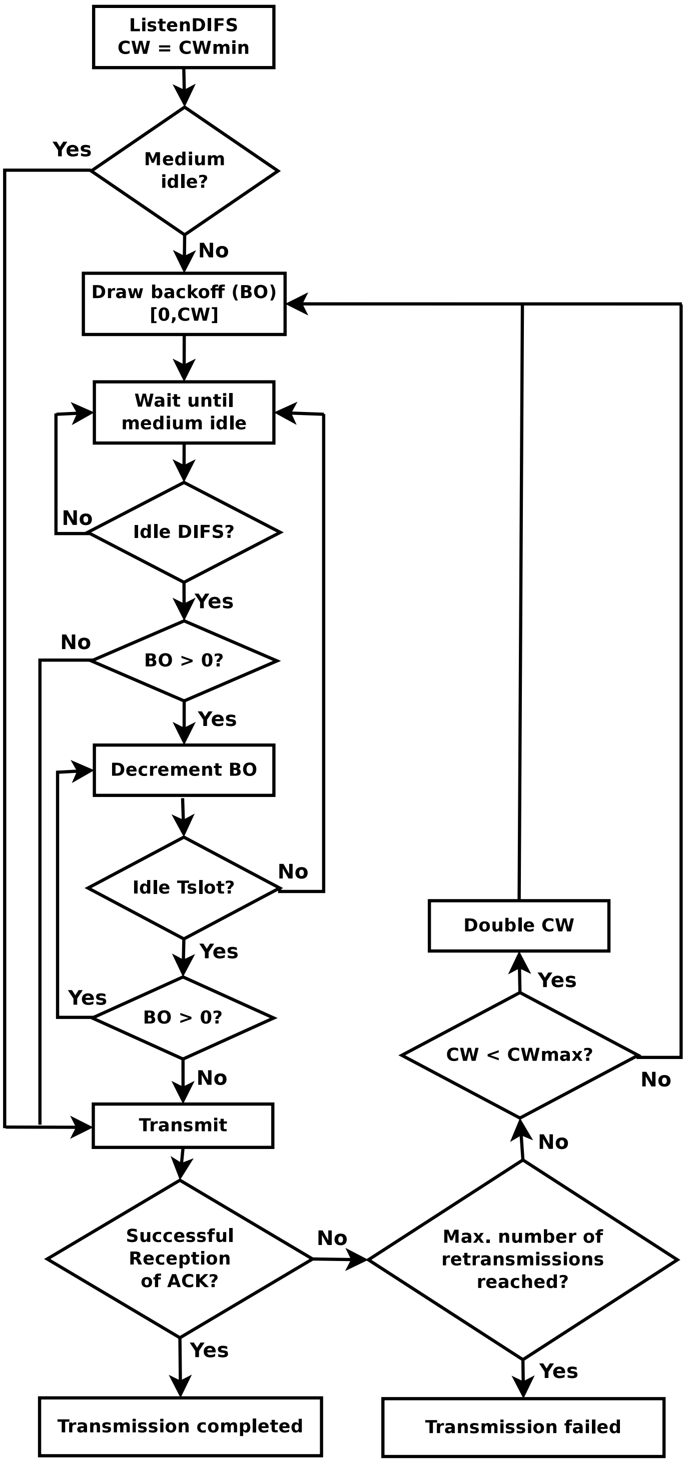


Figure 2.5: IEEE 802.11 MAC protocol mechanisms.

2.1.4 Alternative Solutions to the IEEE 802.11 Standard

A lot of research has been conducted on improving the performance of the IEEE 802.11 by modifying the value of the CW. Actually, many researchers focus on introducing new mechanisms/methods for decreasing the value of the CW that is better than the BEB algorithm. These methods can be categorized into four groups considering that they take into account the traffic load or not (first and second categories), they modify both upper and lower bounds (third category), and changing the CW values by overhearing a collision (fourth category).

The methods of the first group, when a successful transmission occurs, decrease the CW value statically, without considering channel traffic load. An important characteristics of these methods is their simplicity, meaning that they can be easily implemented as a simple upgrade to the IEEE 802.11 standard. MILD [BDSZ94], DIDD [WCP$^+$02, NP00], EIED [SKSM03, SKM05], and LMILD [DVH04] belong to this group. The BEB scheme suffers from fairness issues under high traffic load, and from low-throughput problems when the network size becomes large. The MILD algorithm was introduced to eliminate this problem in the BEB scheme. The MILD scheme increases the CW value by multiplying it by 1.5 and decreasing the CW by one unit. The Multiplication Increase Linear Decrease (MILD) algorithm is conservative and, as a result, it has low throughput when the network load is small. However, MILD works better than the BEB algorithm when the network load becomes large. Exponential Increase Exponential Decrease (EIED) exponentially decreases and increases the CW size, thereby outperforming BEB and MILD in terms of both throughput and delay. Double Increment Double Decrement (DIDD) decreases the probability of packet collision by using a higher CW after a successful transmission instead of resetting it to CW_{min}. It achieves higher packet delay values since it includes the time delay of packets that, otherwise, would have been discarded. However, DIDD does not support Quality of Service (QoS) differentiation between high and low priority applications.

The second group contains methods which introduce Markov models to evaluate the performance of IEEE 802.11. Such methods propose mechanisms to tune the CW size based on the estimated number of nodes by observing the channel status. The methods proposed in [CCG00b, CCG00a, BT03, BFO96, Bia00, DKCH08, BCG04] belong to this group. In such cases, estimation of the number of nodes (or active nodes) requires channel status information. It is obvious that these methods need complex computations that lead to a high power consumption, which is undesirable in wireless ad-hoc networks.

The third group includes methods that modify both upper and lower bounds of the backoff range unlike IEEE 802.11, that increases only the upper bound with each collision. In addition, in these algorithms, the backoff range is divided into several small ranges. The methods presented in [KNGN05, RB06] belong to this group. For example, in [KNGN05], the authors proposed a novel backoff mechanism for associating different CW sizes to different backoff ranges. The mechanism takes both current and past network conditions into account.

The methods of the fourth group contain algorithms that increase the CW value in any node overhearing a collision. Such algorithms are FCR [KFL03] and LMILD. Linear/Multiplicative Increase and Linear Decrease (LMILD) algorithm differentiates between a collision and overhearing a collision, so that colliding nodes increase their contention windows multiplicatively, while other nodes overhearing the collisions increase their contention windows linearly. Also, nodes decrease their contention windows linearly after successful transmissions. For this reason, extra information from the physical layer is required. The fairness performance of the LMILD scheme is better than the BEB scheme. Failures in the detection of packet collisions due to channel fading or by considering other signals as packet collisions may affect the performance of the LMILD scheme. However, it suffers from low throughput in networks with a large number of active nodes. Fast Collision Resolution (FCR) decreases the CW exponentially when it detects a number of consecutive idle slots compared to the IEEE 802.11.

In addition to the previous selection, there are more proposals for improving the performance of IEEE 802.11 by modifying the CW sizes as follows:

Lin et al. [LSHK08] proposed a backoff mechanism called Exponential Linear Backoff Algorithm (ELBA) to improve system performance over contention-based wireless networks. In ELBA, CW size combines both exponential and linear variations, depending on the network load, as indicated by the number of consecutive collisions. In the ELBA scheme, a threshold is set to determine the network load. If the CW size is smaller than the threshold, meaning that the network load is low, the CW is tuned exponentially. Conversely, if the CW size is larger than the threshold, meaning that the network load is high, the CW size is tuned linearly. Numerical results show that ELBA achieves better throughput and collision rates under both light and heavy network loads when compared to other backoff schemes, including BEB, EIED, and Linear Increase Linear Decrease (LILD).

From another perspective, Ekici and Yongacoglu [EY08] investigated the fairness behavior and throughput performance of IEEE 802.11 in the presence of hidden nodes. In particular, they developed a mathematical model which accurately predicts a user's throughput performance and packet collision probability with non-saturated traffic, and on asymmetric hidden node environments. Their model allows observing many interesting results in networks with hidden nodes.

The protocol proposed by Wang and Song [WZ08] uses the NAV information carried in the RTS and CTS packets, in which the sender explicitly indicates the amount of time that the channel will be used for transmission. Therefore, all nodes are capable of updating the NAV based on the RTS and CTS packets from their neighbors, and determining the minimum amount of time for which they should defer their access to the channel. Wang and Song [WZ08] believe that the NAV is a good indicator of the surrounding traffic volume, and therefore they use the NAV count to estimate the surrounding traffic and the impact of the interference suffered by a node. In addition, Li et al. [LTC09] introduced the NAV count in their routing protocol to estimate the intensity of traffic near nodes. The algorithm is improved compared to BEB, as the CWs of backoff mechanism are adjusted reasonably according to the traffic in the WLAN.

Zhang et al. [ZGL08] propose a Dynamic Priority Backoff Algorithm (DPBA) for IEEE 802.11. In the DPBA framework, each node collects statistical data of other node's transmissions while sensing the channel, and maintains a sending data table for all nodes in the network. When a node has data to transmit, it calculates the dynamic priority and contention window according to the number of successful transmissions, and the statistical data in its sending table.

Finally, the algorithm proposed in [LZCS08] (known as Pause-Count Backoff (PCB) algorithm) observes the number of backoff counter pauses during the channel access contention and sets the CW accordingly, based on the estimated results.

However, there is still a need for a low-overhead and dynamic solution that takes network load into account, and that avoids complex computations in order to dynamically adapt the CW values. The methods of the second group consider the network density, but they impose a high overhead. Instead, the methods of the first group have a low-overhead, but do not take network density into account. Moreover, in order to avoid sudden changes in CW values, the previous channel history is a key issue that should be considered.

2.2 Vehicular Ad hoc NETwork (VANET)

2.2.1 Overview

Vehicular environments integrating inter-vehicle communications can be considered as a special form of MANETs where node mobility is road-constrained [HL08]. Vehicular networks are formed by vehicles equipped with wireless devices, called On-Board Units (OBUs), which allow communicating with other vehicles in infrastructure-less wireless networks (vehicle-to-vehicle, V2V) or with roadside units (vehicle-to-infrastructure, V2I), as shown in Figure 2.6.

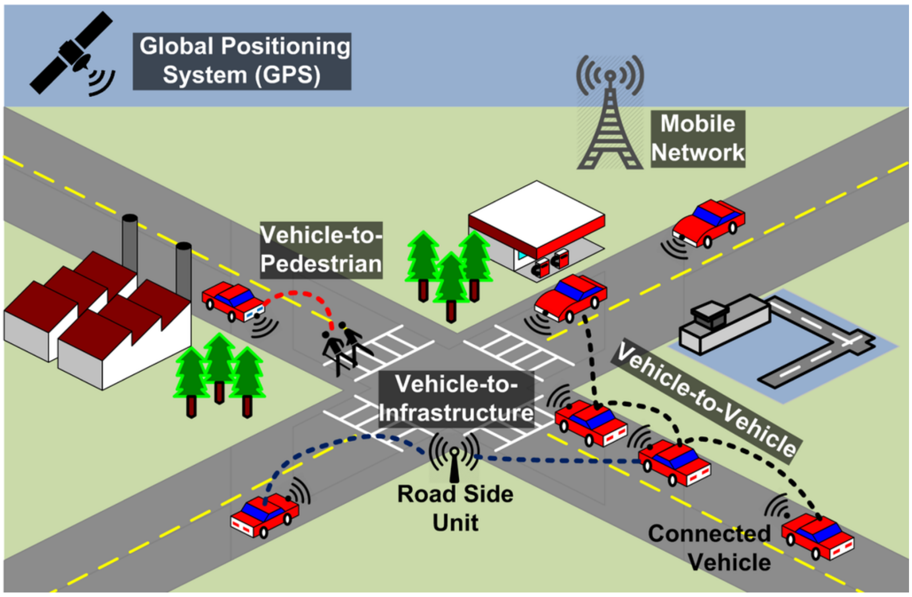


Figure 2.6: ITS V2X communications [HNZ15].

The main differences between VANETs and MANETs have to do with rapid topology changes and diversity of network scenarios. Also, it must be taken into account that, in contrast to MANETs, vehicular density is highly dynamic. For example, in highway scenarios, vehicles have mostly one straightforward direction, but high relative speeds (up to 300 km/h) compared to the cars driving in the opposite direction, which can lead to a challenging situation. In contrast, high-density networks appear in urban scenarios during rush hours. Also, network disconnection can occur in the late night hours or idle daytime hours. Therefore, designing protocols able to take all of these characteristics into account is still a challenging open issue.

Applications for VANETs can be categorized into three groups: safety, convenience (traffic efficiency), and commercial applications (infotainment) [FBS06]; each of these classes of applications has its own QoS requirements. Safety applications represent the main target of inter-vehicle communications. Their goal is to increase each vehicle's awareness about its neighborhood. For this purpose, they use small messages which are broadcasted to a close neighborhood and are limited in time.

The assumed objectives for traffic efficiency applications include reducing the time each vehicle spends on the road in order to reduce both fuel consumption and air pollution. Contrarily to safety applications, these applications do not require a high penetration ratio, and infrastructure requirements can be met by existing 3G/4G networks. Finally, the third group of applications consists of infotainment applications. Although they do not have any effect on road traffic, they provide convenience and comfort to drivers and/or passengers. These applications, similarly to traffic efficiency applications, are mainly infrastructure-based. The delay is not considered as critical as in safety applications, but the transferred data volume is much larger than in safety applications. Figure 2.7 shows some examples of vehicular application scenarios.

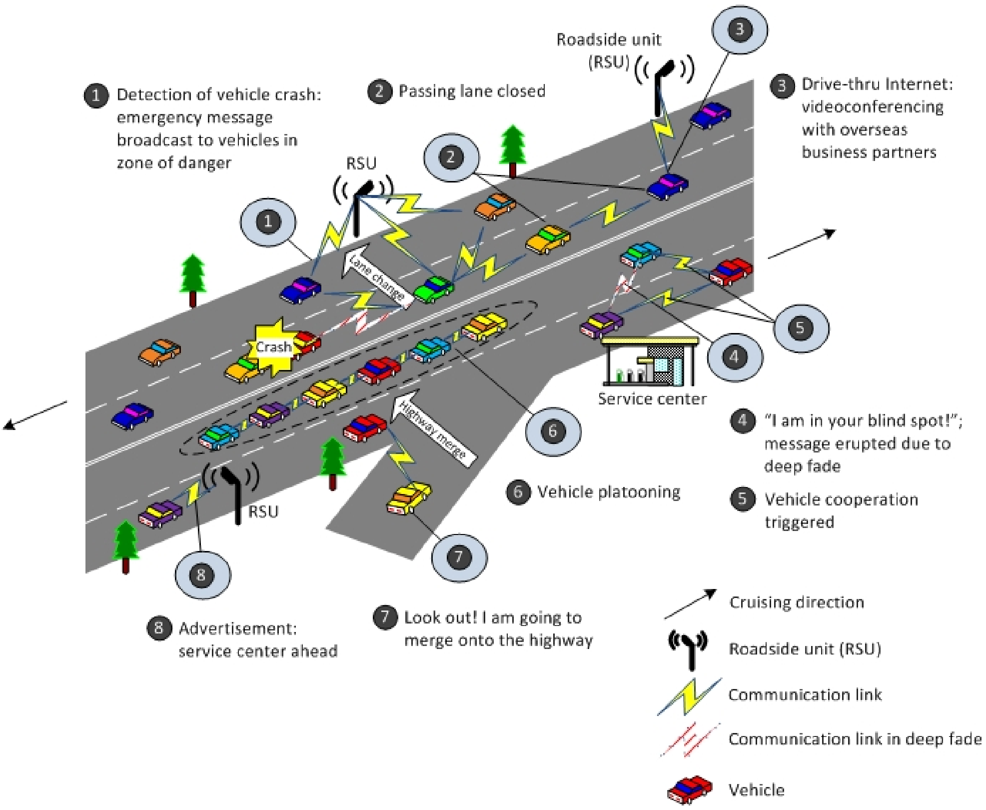


Figure 2.7: VANET applications [TCSZ11].

An application enabled by Cooperative ITS (C-ITS) technology that has received much attention within the research community, as well as by the vehicle manufacturing industry and governmental organizations, is platooning of (heavy) vehicles, which appears tagged as number 6 in Figure 2.7. This application, along with generic scenarios, like highway and urban scenarios, were chosen as backdrop for performance evaluations throughout the thesis. Consider a platoon of tightly spaced vehicles driving on a busy highway. The leading vehicle is operated by a driver, while all following vehicles are operated autonomously once their drivers have joined the platoon and activated the platooning mode. Several studies have shown considerable reductions in fuel consumption by vehicles driving in close proximity in a single lane. In [BF00], Bonnet and Fritz show a 21% fuel reduction for trailing trucks travelling at 80 km/h and an inter-vehicle gap of 10 m. Even the lead truck showed a fuel reduction of 6%. With 5% of the total global carbon emissions accounted to heavy vehicles, the large environmental benefits become a clear incentive for the transport sector.

To support the requirements of different vehicular applications, each vehicle must be aware of the position, status and intention of its surrounding vehicles through message broadcasting. For this purpose, two types of messages are typically used: periodic beacons [ETS14a] and event-driven messages [ETS14b]. Beacons include information such as geographical location, speed, and acceleration, and are only sent to a close neighborhood, as the validity of the information they contain is very limited in time. A large variety of C-ITS based safety applications are built upon the periodic exchange of beacons, and their timely and reliable transmission is vital as a vehicle that continuously fails to deliver its beacon becomes invisible to its neighbors, which may result in potentially hazardous situations. On the other hand, event-driven messages are only generated when an event of common interest occurs, and it is spread within an area of interest for the duration of the event.

Current standardization efforts focus on protocols for inter-vehicle communications in the dedicated frequency band of 5.9 GHz. The two main standards published in U.S. and Europe are Wireless Access in Vehicular Environment (WAVE) [SAE10] and ETSI TC ITS [ETS15]. WAVE encompasses of two standards, the IEEE 802.11p and the IEEE 1609 standards [IEE14], as shown in Figure 2.8. The IEEE 802.11p standard defines the specifications for physical (PHY) and MAC layers, while IEEE 1609 defines additional higher layers as follows: (a) IEEE 1609.1 for application layer; (b) IEEE 1609.2 for enabling security services; (c) IEEE 1609.3 for providing routing and addressing services; (d) IEEE 1609.4 for coordinating different channels; (e) IEEE 1609.5 for layers management; and (f) IEEE 1609.6 for the application facilities management.

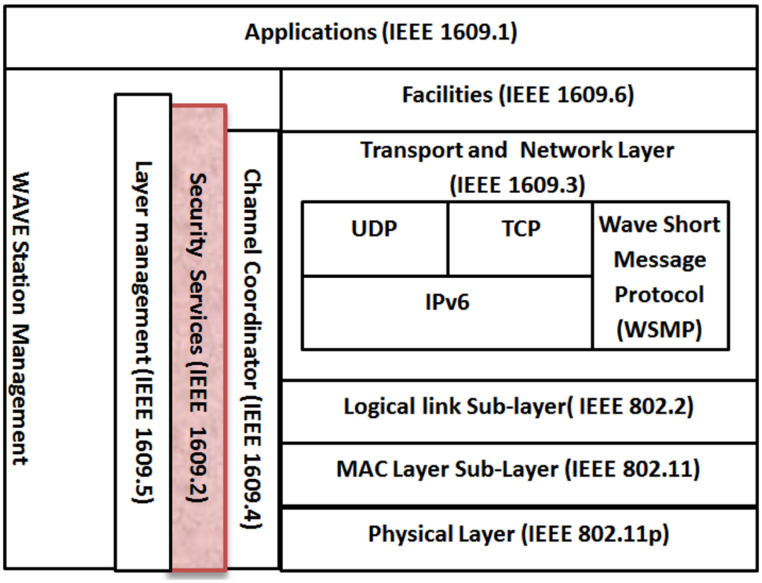
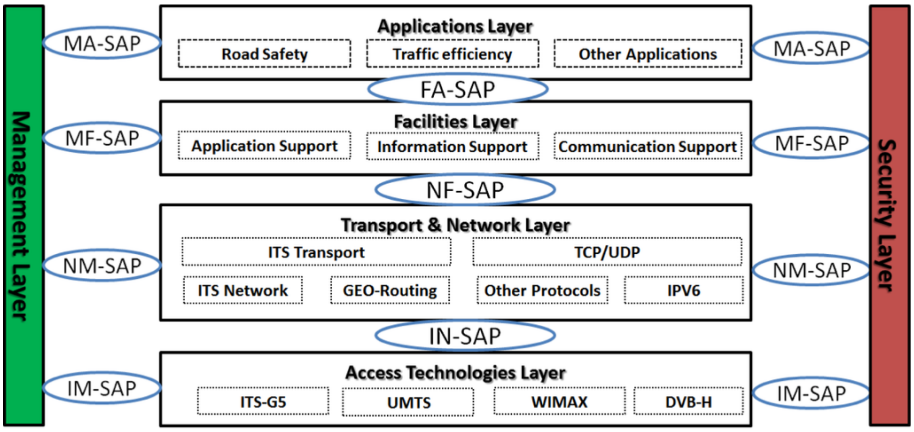


Figure 2.8: WAVE standards for the ITS communications layered architecture [HNZ15].

As shown in Figure 2.9, The ETSI TC ITS standard is similar to the U.S. architecture. It includes a facilities layer located between the network/transport layer and the applications. The session, presentation and application layers have been merged into the facilities layer, which is responsible for generating beacons and event-driven messages on behalf of applications. The access layer consists of two sub-layers: data link and MAC layers. The data link layer follows the IEEE 802.2 standard [IEE98], while the IEEE 802.11p defines both MAC and physical layers. While upper layers are different in ETSI and WAVE, the PHY, MAC, and link layers, which are the focus of this thesis, are identical.



SAP: Service Access Point, **FA**: Facilities/Applications, **MA**: Management/Applications, **MF**: Management/Facilities, **NF**: Networking and Transport/Facilities, **NM**: Networking and Transport/Management, **IN**: Physical Interface/Networking and Transport, **IM**: Physical Interface/Management, **UMTS**: Universal Mobile Telecommunications System, **WIMAX**: Worldwide Interoperability for Microwave Access, **DVB-H**: Digital Video Broadcasting – Handheld.

Figure 2.9: ETSI TC ITS reference architecture [HNZ15].

2.2.2 IEEE 802.11p MAC

Although IEEE 802.11 introduces specifications for wireless networks, it cannot provide optimum performance in vehicular environments. IEEE developed IEEE 802.11p, which is an amendment to the original IEEE 802.11 standard in WAVE, to better support vehicular communications. IEEE 802.11p is an IEEE 802.11-based MAC protocol offering a priority scheme in a similar way to IEEE 802.11e Enhanced Distributed Coordination Access (EDCA) [IEE05], while IEEE 1609.4 manages channel coordination and supports MAC service data unit delivery. IEEE 802.11p proposed a multi-channel operation so that the physical layer consists of seven 10MHz channels, where one of them is Control Channel (CCH), used for safety communications, and the remaining are called Service Channels (SCHs), and they are used for non-safety applications, as shown in Figure 2.10.

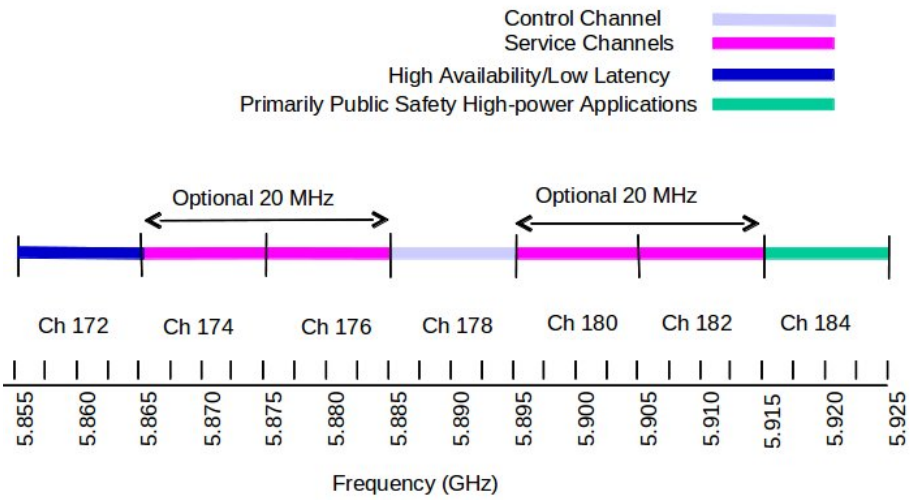


Figure 2.10: IEEE 802.11p Channel Frequency Band.

An Orthogonal Frequency Division Multiplexing (OFDM) modulation scheme is used to multiplex data, similarly to the IEEE 802.11a [IEE99] standard. However, the bandwidth used in each channel by IEEE 802.11p is half of the bandwidth used in IEEE 802.11a. The MAC layer follows the same approach as used by IEEE 802.11e EDCA in order to provide QoS support. The EDCA mechanism defines four different Access Categories (ACs) for each channel compared to just one in IEEE 802.11. Different access categories provide different access priorities, and based on that, they are assigned different contention parameters. For example, AC3, which has the highest priority when accessing the medium, has the lowest Arbitrary IFS (AIFS) and CW values, whereas AC0, which has the lowest priority, has the highest values. Table 5.1 shows the default parameters settings used in IEEE 802.11p for different traffic types. Then, there are six service channels and one control channel, and each of them has four different access categories. So, there are two contention procedures including: internal contentions between different access categories in each channel, and the contention between nodes to access the medium.

Table 2.1: Different application categories in IEEE 802.11p.

AC	CW_{min}	CW_{max}	$AIFSN$
Video traffic (AC3)	3	7	2
Voice traffic (AC2)	3	15	3
Best Effort (AC1)	7	1023	6
Background (AC0)	15	1023	9

2.2.3 Alternative Solutions to the IEEE 802.11p

In the current literature, very few studies address unicast communication in vehicular environments. A fuzzy logic based enhancement to 802.11p is proposed in [CDL11] which adapts the CW size based on a non-linear control law, and relies on channel observation. Furthermore, [JF10] suggests a MAC mechanism which uses a modified version of RTS/CTS in order to estimate network density through message exchange.

Despite the built-in mechanisms of the CSMA/CA MAC protocol to prevent packet collisions, such as listen-before-talk and backoff mechanisms, packets might still collide, which can lead to unbounded channel access delays, especially under heavily loaded channel conditions [BUSB08], [BJU13], [SBJ$^+$14]. Also, when safety messages are transmitted in broadcast mode, no ACK message or RTS/CTS are transmitted to ensure a successful packet reception at the receiver side. Therefore, the IEEE 802.11p MAC protocol is unable to meet the delay and reliability requirements of traffic safety applications.

Several MAC protocols have been proposed in an attempt to improve the communications delay and reliability of the standard approach, e.g., [GS10, STD10, SCB10, DGD12, RPYO11]. For this reason, different authors chose different approaches, such as transmission power, beacon rate, and contention window control. In [GS10], each vehicle counts the number of beacons lost or successfully received in 1 second from neighbouring vehicles, and that value is then used to dynamically adjust the transmission power of periodic beacon messages. The solution proposed in [STD10] changes the beacon generation rate dynamically by considering the channel quality and the importance of the message, while using infrastructure networks in the proximity. Also, [SCB10] suggested a method to modify the backoff time for controlling network congestion. The proposed methods rely on dynamically adjusting the minimum threshold of the contention window to determine an optimal backoff time. It starts with a relatively large value for the contention window, and then divides it by two every time a safety message expires. However, the optimum contention window size remains unclear. In [DGD12], the authors proposed a beaconing congestion solution which detects congestion based on the continuous monitoring of different parameters including medium busy time, packet collision rate, and beacon reception rate. When the network is detected as congested, the protocol adjusts its transmission power and beacon generation rate, thereby decreasing the beaconing load. In [RPYO11], the authors propose a technique that dynamically adjusts the transmission power and the contention window size based on the vehicle's local traffic density. It calculates the transmission range based on the traffic density, and then it uses that range to determine the power level. Also, different contention window sizes are selected based on the message content.

Due to the inherent drawbacks of CSMA-based MAC protocols, all previous approaches cannot be a good choice for low-latency safety applications in VANETs. To address this problem, Time Division Multiple Access (TDMA) and Space Division Multiple Access (SDMA) based techniques [BUSB09, OZL13, AARS09, LLLC11, HMW15] have recently received much attention in the VANET literature because they are able to provide guaranteed delay. TDMA-based schemes rely on assigning different time slots to vehicles that are closer to each other in order to minimize the contention chances among vehicles, reusing the same slot times for the farthest vehicles. For example, [OZL13] proposed a multichannel TDMA-based MAC (VeMAC) protocol to assign disjoint sets of available time slots to vehicle nodes moving in opposite directions, and to RSUs. However, the mechanism considers vehicle nodes and RSUs as being the same, and it ignores the functionality of RSUs as coordinator nodes. A common problem of TDMA-based mechanisms is that they use fixed length frames, and so two or more vehicles can reserve the same slot. Although some improvements have been proposed to solve these problems and make such approaches more compatible with vehicular environments, they still require additional efforts.

In SDMA-based techniques [JKN14, AARS09, LLLC11], the road is divided into subsets which are called cells. A particular set of time slots are assigned to each cell, so that each vehicle chooses its time slot based on its location on the road. For example, [JKN14] proposed a technique for SDMA approaches to permit multiple transmissions per road segment using the CSMA/CA mechanism in each segment in order to improve both space and bandwidth usability. The main problem of SDMA-based schemes is time scheduling complexity; in addition, their resource utilization efficiency decreases in VANETs due to unbalanced traffic density and dynamic topology changes. The effectiveness of these two types of MAC protocols have already been compared by several authors [BUSB09], [SUS11], [SCB10].

The overall results show that TDMA-based solutions provide several benefits [HML$^+$15], including: high reliability, deterministic access time, efficient channel utilization, and equal access to the channel for all vehicles. However, these methods typically require slot synchronization, and they are not very dynamic when it comes to changing the beacon period or scheduling retransmissions. Even if they are able to provide adaptability, a high level of coordination and overhead are still required [OZL13, DDN$^+$14]. Similarly, retransmissions usually introduce additional overhead for control data and scheduling, and also a centralized control unit to determine if retransmissions are needed, and when.

The token passing method can be implemented on top of IEEE 802.11 to offer QoS provisioning in terms of reserved bandwidth and bounded delay when operating under high node densities. The Wireless Token Ring Protocol (WTRP) [ELSV04] was the first scheme using this idea in vehicular environments. However, it is still incapable of adapting to the fast topology changes typical of these environments. In [XYJ07], a Wireless Dynamic Token Protocol (WDTP) was presented which defines different subsets, of vehicles and, in each subset defines a master node responsible for token management. In [WZ08], a token-based scheduling scheme is presented where vehicles do not have to maintain an ordered list of their neighbour nodes, and where each vehicle stochastically passes the token to others. Nevertheless, the authors assumed that the network is fully-connected, which is not the case in VANETs. In [ZLS08], an Overlay Token Ring Protocol (OTRP) is presented for vehicular environments. It operates in two modes: in the ordinary mode, beacons circulate among the neighbouring nodes, while the other mode, known as emergency mode, is used in case of an accident. By adapting the token passing solution and using different modes, OTRP achieves better performance and rapid emergency message delivery in VANET environments. However, the authors did not consider some issues which are very challenging in VANETs, such as interferences among different rings. Also, the simulation environment was restricted to only a few nodes, and they used a proprietary C++ based simulator that prevents the research community from doing a thorough validation. In [BLC$^+$09], a Multi-Channel Token Ring MAC Protocol (MCTRP) is presented for inter-vehicle communications. In MCTRP, vehicles are grouped into rings based on their speed. Since this protocol has to make groups and central vehicle election very frequently, it introduces a high overhead, which makes it unsuitable for high-speed networks.

Although these proposals seek to keep channel access delay and packet loss at acceptable levels, they are designed to obtain benefits for generic vehicular ad hoc networks, not tailored towards the specific requirements of a platooning application. Specific strategies to improve timing and reliability in platooning have been considered in the literature. In [FN12a] the authors suggested two different technologies: IEEE 802.11p for the event-driven type of messages, and Infra-Red (IR) for beacon broadcasting to improve reliability. Böhm et al. studied the coexistence of beacon and event-driven messages, showing how the choice of different MAC layer priority classes for beacon and event-driven messages, along with an adequate dissemination strategy for event-driven messages, can avoid overloading the medium with unnecessary data traffic and improves performance [BJU13]. In [BK15], the authors introduced a general communication framework for centralized channel access and retransmission capabilities for safety-critical inter-platoon communications based on the data age of previously received messages. Also, they argue that the service channel should be used for intra-platoon communications to provide the required level of reliability. Segata et al. showed that a combination of slotted scheduling and transmit power control mechanisms can improve reliability for platooning scenarios [SBJ$^+$14]. Moreover, Fernandes and Nunes [FN12b] analyze five different TDMA-based MAC protocols to improve reliability for platooning scenarios. They suggest the use of priority levels and anticipatory information from all platoon members to improve the reactivity to, e.g., speed changes.

However, a novel MAC solution that does not require synchronization nor extra overhead for scheduling of control traffic (TDMA-based methods) has to be proposed for both general and platooning applications. Token-based methods showed that they can achieve significant enhancements, but they must be adapted to the fast topology changes typical of vehicular environments. The proposed solution should also be decentralized, adapting easily to changes in the beacon frequency. Furthermore, it must support both beacons and event-driven messages, with high reliability and low delay.

2.3 Simulation Tools

2.3.1 Network Simulation Tools

Currently we can find several network simulators that can be used for both MANET and VANET simulations. In the following we will discuss the characteristics of these simulators, and attempt to determine which one can be more adequate for simulating vehicular scenarios.

2.3.1.1 OMNeT++

OMNeT++ [Var99] is a C++ based, open source, and discrete event network simulator with strong Graphical User Interface (GUI) support. It can be used for modeling any system which can be described as a queuing system. Since OMNeT++ is a simulation framework, it does not provide models for wireless network simulation. Therefore, several frameworks have been developed on OMNeT++ for simulating mobile ad hoc networks. Among all of these frameworks, INETMANET [INE10] and MiXiM [KSW$^+$08], which include propagation models specially designed for vehicular environments, are the most appropriate ones for VANET simulation [SEGD11].

Each model in OMNeT++ is composed by a set of reusable components termed modules. OMNeT++ allows users to use two types of components: simple and compound modules. The functionality of each simple module is defined by C++ code, and it uses a simulation library. These simple modules can be combined unlimitedly like LEGO blocks to make compound modules. Simple modules can be connected with links, which connect two gates of two different modules to each other. Gates are input and output interfaces of modules. Connections are created within a single level of module hierarchy. Connections spanning different hierarchy levels are not permitted, as they would prevent model reuse. Modules communicate with each other through messages, which carry arbitrary data. Messages travel through a chain of connections, starting and arriving in simple modules. Messages can contain some information from other modules or be sent to the same module (self-messages) in order to implement a timer. In Figure 2.11, boxes represent simple modules (gray background) and compound modules. Arrows connecting small boxes represent connections and gates.

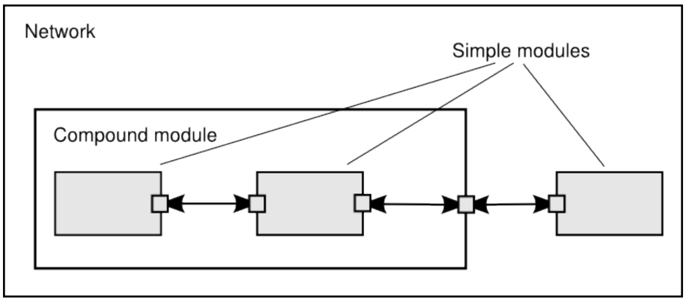


Figure 2.11: Simple and compound modules in OMNeT++.

Some of the features of OMNeT++ are:

- Possibility of designing modular simulation models, which can be combined and reused flexibly.
- Composing models with any granular hierarchy.
- Availability of extensive simulation libraries that include support for input/output, statistics, data collection, random number generation and data structures.
- C++ based simulation kernel, which allows using it in larger applications.
- Graphical simulation configuration interface using NED and omnetpp.ini without requiring the use of scripts.

The main problems of this simulator in order to be a suitable simulator for VANETs are the lack of models for wireless networks, and the lack of an integrated mobility manager. Therefore, a mobility manager and a framework in order to support models for wireless communications must be installed to provide these key functionalities when attempting to achieve a realistic VANET simulation environment. In this thesis, we chose this simulator coupled with the INETMANET or MiXiM frameworks along with SUMO in order to provide realistic vehicular scenarios. INETMANET is an open-source package which provides network simulation models for OMNeT++. Although it focuses on the high level of the protocol architecture for wired and wireless communications, it also includes MAC layer protocols similar to IEEE 802.11p. Another option is to use this package in conjunction with the MiXiM package. MiXiM implemented detailed wireless NICs, so using these two packages together provides a detailed implementation at all levels of the protocol architecture. Also, SUMO is used to generate real vehicular traffic in road networks, as presented in Section 2.3.2.1.

In summary, for each simulation using OMNeT++, the following parts must be described:

1. Simple modules (provided by some packages like INETMANET, MiXiM, etc).
2. Topology (using NED files).
3. Simulation configuration (using omnetpp.ini).

2.3.1.2 Network Simulator 2/3 (NS-2/NS-3)

NS-2 [NS289] is a discrete event simulator developed by the VINT project research group at the University of California at Berkeley, with support of the US Defense Advanced Research Projects Agency (DARPA). It is assumed as the standard simulator for wired networks due to the large number of models that have been developed for this simulator. It was extended by the Monarch research group in Carnegie Mellon University in order to be able to model node mobility, and more realistic PHY and MAC layers (IEEE 802.11) for wireless networks. Several mobility and radio propagation models exist in NS-2 which can be used, but none is designed for VANET simulation. Some new models have been produced for VANET simulation in NS-2, but still there are some disadvantages of using NS-2, including: its high complexity makes the implementation of vehicular mobility models difficult inside the framework; also, its memory and CPU consumption do not allow simulating large scenarios.

NS-3 [NS314] is an optimized version of NS-2 which introduces less complexity by removing the C++/TCL interactions used by NS-2, thereby allowing it to handle large-scale scenarios. However, it cannot use the many models developed for NS-2, which is a negative point for NS-3.

2.3.1.3 Other Network Simulators

QualNET:

Global Mobile Information System Simulator (GloMoSim) is an open source and scalable simulator for wireless and wired environments developed at the University of California in Los Angeles. The layered design of this simulator, with different APIs between them, eases the integration of different layers by different people. The GloMoSim project stopped in 2000, and a commercial version, QualNET [QUA15], has been maintained since then. The QualNET framework is able to simulate large scale scenarios with several thousand nodes. Also, a new VANET mobility model, called CORNER [GFPG10] has been recently added which makes it as a good choice for VANET simulation, but its commercial orientation limits its wide usage.

SWANS:

Java in Simulation Time (JiST) [JIS05] is a general-purpose discrete-event simulator written in Java, developed at the Cornell University, and the Scalable Wireless Ad hoc Network Simulator (SWANS) is an extension to this simulator that has been specially designed for MANETs. SWANS is able to simulate large scenarios of more than 10,000 nodes. The interesting point of this project is that the real applications written in Java can be directly tested with this simulator. The disadvantages are that the project is no longer maintained, and that it does not include any mobility or radio propagation model for VANET simulation.

2.3.2 Traffic Simulation Tools

Traffic flow simulations can be divided into 3 groups depending on the level of details, as shown in Figure 2.12. In macroscopic traffic models, the flow is assumed as the basic entity. The next group includes microscopic traffic models in which more details are implemented, so that vehicles are the smallest entities. This type of traffic models is common in vehicular network simulations. The last group includes sub-microscopic traffic models in which the inner parts of each vehicle are also implemented, including: engine, gear-box, and so on. However, since this type of traffic models introduces too much computational overhead, they are not considered as a suitable option for large-scale network simulations, like VANETs.

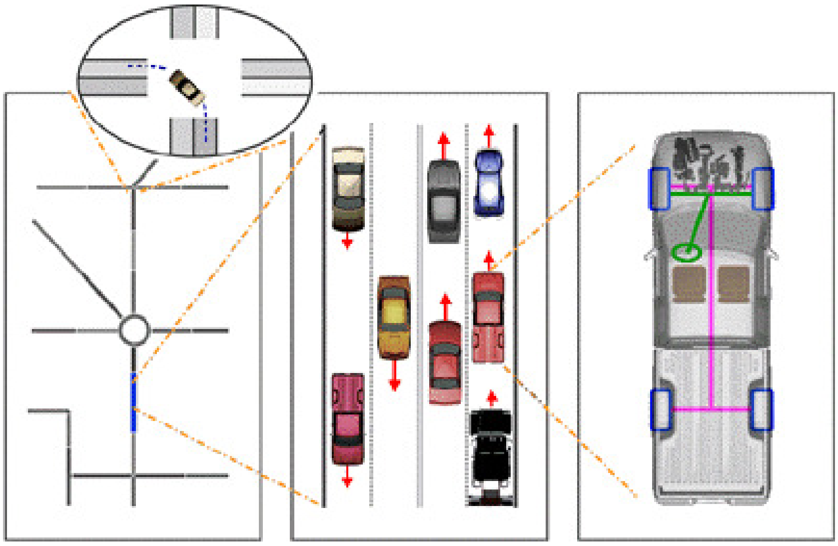


Figure 2.12: The different simulation granularities; from left to right: macroscopic, microscopic, sub-microscopic (within the circle: mesoscopic) [SUM15].

There are several traffic simulators which are able to generate vehicular mobility. However, in this section, we only consider simulators which are still updated and supported in different operating systems. For example, CORridor SIMulation (CORSIM) [KSK14] and Verkehr In Stadten SIMulationsmodell (VISSIM) [VIS15] are only supported in a Microsoft Windows platform, which is a negative point for network researchers that usually prefer the Linux OS. Also, the MObility model generator for VEhicular networks (MOVE) [Kar07], which was built on top of SUMO, is no longer maintained.

2.3.2.1 SUMO

Simulation Of Urban Mobility (SUMO) [BK11] is an open source, microscopic traffic simulator specially designed to handle large scale vehicular mobility. It supports three different types of elements: vehicle types, trips, and routes. A *Vehicle type* specifies the physical properties of a typical vehicle in the simulator. A *Trip* defines the departure time and the destination edge, while *route* expands *trip* by defining all the edges through which a vehicle will pass. In general, we must provide different files to SUMO in order to define the simulation map, the obstacles, and the routes used. The simulation map can be either synthetic or a real map extracted from openstreetmap.org [OPE15].

2.3.2.2 VanetMobiSim

VanetMobiSim [FHFB07] is an extension to the CANU Mobility Simulation Environment (CanuMobiSim) [CAN05], and it was specially designed for modeling vehicular mobility. It has the ability to import maps and produce mobility traces with different formats, supporting different simulation and emulation tools for mobile networks. Vehicular mobility patterns can be based on random trips or an origin/destination approach. It supports an enhanced version of IDM including both Intersection Management (IDM/IM) and Lane Changing (IDM/LC), and also an overtaking model (MOBIL) [TK09].

2.3.3 Interlinking Tools

In this section, we describe different modules used to make an interaction between a network and a traffic simulator. As mentioned before, one of the important challenges in VANET simulation is that the mobility of a node is not independent from other nodes, being affected by its surroundings. Therefore, the traffic simulator must be able to change the initial trace file during the simulation based on the feedback received from the network simulator. Below we summarize some modules created to link some commonly used simulators like NS-2, OMNeT++, and SUMO.

2.3.3.1 Veins

Vehicles in Network Simulation (Veins) [SGD11] is considered as the best package for VANET simulation, especially at the MAC level. It produces a Transmission Control Protocol (TCP) connection in order to provide an interaction between SUMO and the MiXiM framework from OMNeT++. In Veins, the network simulator is able to influence the vehicles' movements produced by the traffic simulator by exchanging some commands.

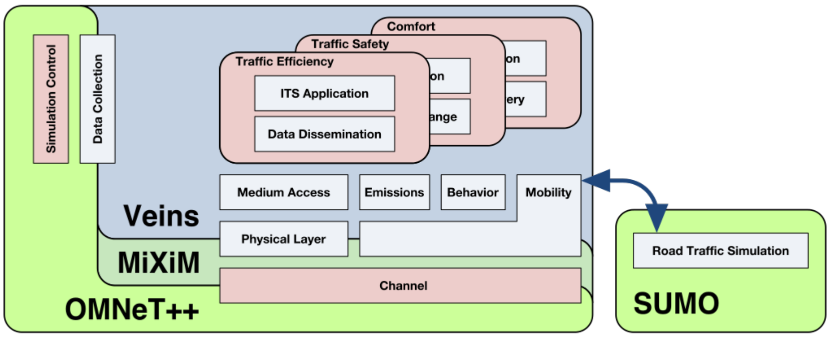


Figure 2.13: Architecture of Veins [VEI15].

2.3.3.2 Other Interlinking Tools

TraNS and iTetris:

Traffic and Network Simulation Environment (TraNS) [PRL+08] was the first tool using a link between a network and a traffic simulator, but it is not a high performance framework, it does not support new versions of SUMO, and it is no longer maintained (since 2008). The Integrated Wireless and Traffic Platform for Real-Time Road Traffic Management Solutions (iTetris) [ITE10] is seen as the successor of TraNS, so that it couples NS-3 and SUMO through a central control block named iTetris Control System (iCS).

VsimRTI:

Unlike the aforementioned interlinking tools, V2X Simulation Runtime Infrastructure (VsimRTI) [Sch11] is a generic framework that can be used by different simulators such as VISSIM, SUMO and JiST/SWANS. Also, this project can work as an emulator for directly testing real applications in V2X environments.

2.3.4 VANET-Specific Simulation Tools

As we mentioned before, VANET simulations require modeling the drivers' behavior in detail, as well as radio channels. Also, integrated frameworks for simulating both mobility and networking are clearly needed for effectively evaluating the performance of vehicular systems. In this section, we describe the simulators that have been specially designed for vehicular communications.

GrooveNet [MWR+06]:

This simulator was developed at the Carnegie Mellon University, and it is a hybrid simulator which enables communication between real and simulated vehicles. It has a powerful GUI and the ability to import maps. Although it has several communication protocols implemented, its complexity and lack of documentation make its development a rather difficult task.

NCTUns:

National Chiao Tung University Network Simulation (NCTUns) [WCC+07] is also a hybrid simulator like GrooveNet, and it was the first simulator to implement the complete IEEE WAVE architecture. The advantages of this simulator are: it can directly run real applications because it uses the real Linux Transmission Control Protocol (TCP)/Internet Protocol (IP) protocol stack, and it supports parallel simulation on multi-core machines. The disadvantages are: it is only compatible with the Fedora 9 Linux distribution, and it went commercial in 2011.

IWIS:

Integrated Wireless Intersection Simulator (IWIS) [JBE+08] is a tool that was not widely adopted because it was specially designed for intersection management. It provides detailed information for propagation models by considering urban elements. Also, it models several VANET MAC layer protocols.

Chapter 3

IEEE 802.11-based MAC Protocols

3.1 Introduction

In this chapter we propose different enhancements to the IEEE 802.11 and 802.11p MAC protocols. We begin by detailing our proposals for MANET and VANET environments. We then proceed by assessing how our proposals outperform the available standards and other existing solutions through computer simulations. We conclude this chapter by showing that our proposals achieve better performance at supporting unicast applications compared to the state of the art.

3.2 IEEE 802.11-based MAC Protocol for MANETs

In the IEEE 802.11 MAC protocol, fast changes in CW values entail high collision rates when the number of nodes is high, which has a significant impact on network performance. To tackle these issues, we propose two solutions where the past history concerning network conditions is taken into account for smoothly adjusting the CW size. The difference between these two methods is that one of them, Dynamic Deterministic Contention Window Control (DDCWC), divides the overall backoff range [0, CW_{max}] into several small ranges and assigns each backoff subrange to a particular collision resolution level, thereby adjusting both upper and lower bounds of the backoff range. The other one, History Based Contention Window Control (HBCWC), keeps the same lower bound for the contention windows in all nodes, similarly to IEEE 802.11, and modifies the upper bounds based on the channel traffic load. It is noteworthy that the proposed CW control schemes do not take into account collisions occurred during the transmission of control packets like RTS and CTS.

In the following sections, we explain the similarities of these two methods, and then individually describe their differences. Since both of the proposed methods require to maintain the channel history, the channel condition is checked regularly and the result is stored in a Channel State (CS) vector.

In both proposed solutions, the CS vector plays an important role as it shows the network condition using a three-element array that is updated upon each transmission attempt. The channel state is monitored by invoking function *is_ idle()*. If function *is_ idle()* returns zero it means that the channel is busy, and when it returns one, it means that the channel is free. When the new channel state is stored, the oldest one in the CS array is removed and the remaining stored states are shifted to the left. Figure 3.1 shows how the CS vector is changed based on the results of the *is_ idle()* function. For example, successful transmission (no collisions) causes a transition from stage (or status) 000 to stage 001 and, if collisions occur, we have a transition from stage 001 to stage 010.

The selection of the length of the channel state vector is a challenging design decision. For example, if we choose a longer vector (array), it will have a large overhead. On the contrary, if we choose a smaller vector (array), it will not be able to show the network condition. Based on our simulation experiences, we chose a three-element CS array.

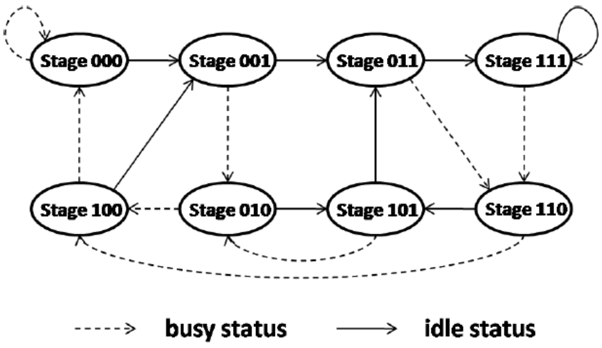


Figure 3.1: CS vector updating diagram.

3.2.1 First Solution: HBCWC

In HBCWC, after each packet reception, the CS vector is checked to modify the CW size based on Table 3.1. Therefore, it doubles the CW size when the packet is lost, similarly to IEEE 802.11, except for the case where the CS array contains two consecutive ones before the new state, in which case the CW size is instead multiplied by A, thereby gradually increasing the CW values to improve the overall performance. In addition, and similarly to IEEE 802.11, the CW values are set to the CW_{min} when a successful transmission is detected. Parameter A is initially set to 1.5.

Table 3.1: Contention window calculation in HBCWC.

Status	**CW range**
000	
010	CW = CW ×2
100	
110	CW = CW $\times A$
xx1	CW = CW_{min}

3.2.2 Second Solution: DDCWC

Similarly to HBCWC, DDCWC also maintains the channel history through the CS vector, but DDCWC splits the backoff range and assigns different ranges to different network stations. More details about how DDCWC adjusts the CW sizes is explained in the following.

We split the total range [CW_{min}, CW_{max}] into different ranges, where each range is associated to a contention level (CS vector status). For each contention level, the lower bound (CW_{lb}) and the upper bound (CW_{ub}) of the contention window are selected based on Equations 3.1 and 3.2.

$$\mathrm{CW}_{ub}(\mathrm{i}) = CW_{ub}(\mathrm{i\text{-}1})\times z \tag{3.1}$$

$$\mathrm{CW}_{lb}(\mathrm{i}) = CW_{ub}(\mathrm{i})\text{-size} \tag{3.2}$$

In Equations 3.1 and 3.2, i indicates the network contention levels, which varies between 1 and 8 since the CS array has three elements in our scheme. z is a specific number in our scheme and *size* is the range size. Different values for z and *size* were chosen by performing eight repetitive simulations and modifications to the DDCWC scheme. The results are shown in Table 3.2.

The CS array is initialized with value 111. The initial values for CW_lb and CW_ub are 0 and CW_{min}, respectively. After each transmission attempt, the boundaries and size of the range are updated according to Table 3.2, which is achieved based on Equations 3.1 and 3.2. Parameters A, B, C, which are used in order to calculate the CW values in Table 3.2, are set to 2.1, 0.6, 1.7, respectively.

The node checks function *is_ idle()* when it has a new packet for transmission. If the channel is sensed idle, the CS array will be set to one, change the backoff range, and start its defer timer with DIFS. Otherwise, we insert a value of zero in the CS array, change the backoff range, and wait for the channel to become idle. After a DIFS period, the channel is sensed again. We follow a similar procedure to the one mentioned above. If the channel is found idle again, the node will transmit.

Table 3.2: Contention window calculation in DDCWC.

Status	**CW range**
000	$CW_{ub} = CW_{ub} \times A$ $CW_{lb} = CW_{ub}$-96
001	$CW_{ub} = CW_{ub} \times B$ $CW_{lb} = CW_{ub}$-32
010	$CW_{ub} = CW_{ub} \times C$ $CW_{lb} = CW_{ub}$-64
011	$CW_{ub} = CW_{ub} \times C$ $CW_{lb} = 0$
100	$CW_{ub} = CW_{ub} \times A$ $CW_{lb} = CW_{ub}$-64
101	$CW_{ub} = CW_{ub} \times B$ $CW_{lb} = CW_{ub}$-32
110	$CW_{ub} = CW_{ub} \times C$ $CW_{lb} = CW_{ub}$-32
111	$CW_{ub} = CW_{ub} \times C$ $CW_{lb} = 0$

3.3 IEEE 802.11p-based MAC Protocol for VANETs

As mentioned in Section 2.1.4, in IEEE 802.11-based MAC protocols, a significant reduction of the network performance stems from the lack of ability to select an optimal CW size, especially in dense traffic networks. To solve this problem, we propose a new method, Density Based Method for Adjusting the CW size (DBM-ACW), to select the CW size based on the network traffic density. In this method, channel conditions are observed based on the packet transmission status, and the result is stored in a channel state vector. This vector must be updated after each transmission attempt. A significant part of the protocol relies on how the channel condition is captured by the CS vector, and how this vector is then used to update the CW size in order to improve throughput, which is the key contribution of this work. These two issues will be further explained in the following sections.

3.3.1 Initialization

The CS vector, that is introduced by our protocol and used for keeping track of channel conditions, is initially set to one in order to assume a collision free environment. The proposed approach relies on a set of parameters to optimally adapt the CW size to network density, as detailed in Algorithm 2. These parameters must be set in this step. A more detailed discussion on how these parameters were

Algorithm 1 Time-out expiration or ACK reception.

```
1: Shift the CS array to the right by one
2: if receiving a time-out or a corrupted ACK packet then
3:     $CS_0 = 0$
4: else
5:     $CS_0 = 1$
6: Adapt()
```

obtained is presented in section 3.3.3.

3.3.2 The Channel State Vector

In 802.11-based MAC protocols, and after each data frame transmission, each node sets its timer and waits for an acknowledgement. In DBM-ACW, upon each timer expiration, or upon receiving a packet, Algorithm 1 is called. This algorithm basically behaves as follows: if the transmitter receives an ACK frame from the receiver, a value of 1 is inserted into the CS vector (Line 5); otherwise, if a collided/faulty frame is received, or if the transmitter waiting timer expires before receiving the acknowledgement, a zero value is inserted into the CS vector (Line 3). Note that we assumed that one service channel is assigned for our application, which means that the broadcast traffic in the control channel cannot affect the performance of our protocol.

The CS vector is updated by shifting before setting the CS_0 value (Line 1). After setting the CS vector, function Adapt (Algorithm 2) is called in order to adapt the CW. Based on extensive simulation results, we chose a three-element array in order to achieve a trade-off between overhead and performance. If a smaller array is chosen, it will fail to assess the real network conditions, while larger array values do not lead to significant performance improvements.

3.3.3 Changing the Contention Window Size

Upon each timer expiration or packet reception, Algorithm 2 is called in order to update the value of the CW. Upon each packet loss, timer expiration or collision, the CW size is increased. DBM-ACW multiplies the CW value by 2 in order to obtain the highest packet delivery ratio, except for the case in which the CS array contains two consecutive ones before the new state; that particular situation means that we observed two successful transmissions before detecting an unsuccessful transmission. In that case the CW is multiplied by parameter A (Line 3).

In DBM-ACW, the CW size is set to the minimum CW, CW_{min}, upon each acknowledgement reception, except for the case in which the CS array contains two consecutive zeros before the new state, which means that two unsuccessful transmissions are observed before detecting a successful transmission. In that case the CW is multiplied by parameter B (Line 8).

Algorithm 2 details how the CW size is chosen in our DBM-ACW scheme. Depending on the channel congestion severity, the current CW size is multiplied

Algorithm 2 Adapt

```
if $CS_0 = 0$ then
    if $CS_1 = 1$, $CS_2 = 1$ then
        CW = $CW \times A$
    else
        CW = $CW \times 2$
else
    if $CS_1 = 0$, $CS_2 = 0$ then
        CW = $CW \times B$
    else
        CW = $CW_{min}$
```

by a value in the range from 0.2 to 2, or set to CW_{min}. The upper bound is selected as in IEEE 802.11p, so that the CW size is multiplied by 2 when the channel is detected as busy or a collision has occurred. When the channel is very congested, the current CW size is multiplied by a value in the range from 1.1 to 2 in order to decrease the probability of selecting the same backoff number. Otherwise, when the channel density is low, the current CW size is multiplied by a value in the range from 0.2 to 1.1, or set to CW_{min} in order to avoid waiting for a long time when channel occupation is low. The parameter values can be controlled based on the network traffic density during the simulation but, in order to decrease the protocol overhead, we decided to fix these values before the simulation. Therefore, we repeated the simulation using different combinations of values to obtain the best performance. Based on extensive simulations, the optimal value for parameters A and B was found to be equal to 1.7 and 0.8, respectively.

3.4 Performance Evaluation

In this section we assess the effectiveness of the proposed MAC solutions HBCWC, DDCWC, and DBM-ACW at supporting constant bit rate traffic. HBCWC and DDCWC are evaluated in a typical MANET environment, and under different network traffic densities. In addition, the performance of DBM-ACW is evaluated by comparing it against IEEE 802.11p and HBCWC in vehicular network scenarios.

3.4.1 Simulation Settings and Results for DDCWC and HBCWC

NS-2 (version 2.28) is used for network simulations. The simulations are based on a 1000 by 1000 m flat scenario with 50 wireless nodes. The simulation time was set to 600 seconds. Each node generates constant bit-rate traffic. The size of the data payload is 512 bytes, and each node generates data packets at a rate of 4 packets per second. The propagation range for each node is 250 m, and channel capacity is 2 Mb/s. We utilized the random waypoint model as the mobility model. The minimum node speed for the simulation is 0 m/s, while the maximum speed is

Table 3.3: The simulation parameters.

Simulation Parameter	**Value**
Propagation model	Two ray ground
Routing protocol	DSR
Number of nodes	50
Simulation time	600 sec
Simulation environment	1000 $\times 1000m$
Transmission range	250 m
Channel capacity	2 Mb/s
CBR packet size	512 byte
CBR data rate	4 packet/s
CW_{min}	31
CW_{max}	1023
Error rate	0.1 packet/s
Min speed for waypoint model	0 m/s
Max speed for waypoint model	20 m/s
Pause time for waypoint model	50 sec

20 m/s. Pause time is set to 50 seconds. Table 3.3 summarizes the simulation parameters.

The metrics used to evaluate the performance of the MAC solutions under study were similar to those used in previous studies. They are summarized as follows: (a) Packet Delivery Ratio (PDR), which represents the ratio of the total number of packets received by the final destination and the packets originated by the source; and (b) average end-to-end delay, which represents the average time required for a packet to travel from source to destination.

Figures 3.2 and 3.3 represent the PDR, and average end-to-end delay in seconds, for the IEEE 802.11 MAC standard and our new solutions, HBCWC and DDCWC, when the number of connections varies from 10 to 50. In these figures, we clearly observe that the packet delivery ratio for our proposed methods is improved compared to IEEE 802.11. Furthermore, our DDCWC proposal also improves the HBCWC performance since DDCWC assigns different backoff ranges based on the channel status, avoiding to reset the CW to the minimum value.

Our proposed solutions also improves the average end-to-end delay compared to the IEEE 802.11 MAC, as shown in Figure 3.3. When the number of connections is large, DDCWC shows higher delays compared to HBCWC, since DDCWC gradually decreases the CW value upon a successful transmission. This means it has to wait for a longer time to be able to transmit messages. This issue leads to decreases in the number of collisions, thereby improving the reliability, but it suffers from higher longer delays than HBCWC since the latter resets CW values, similarly to IEEE 802.11.

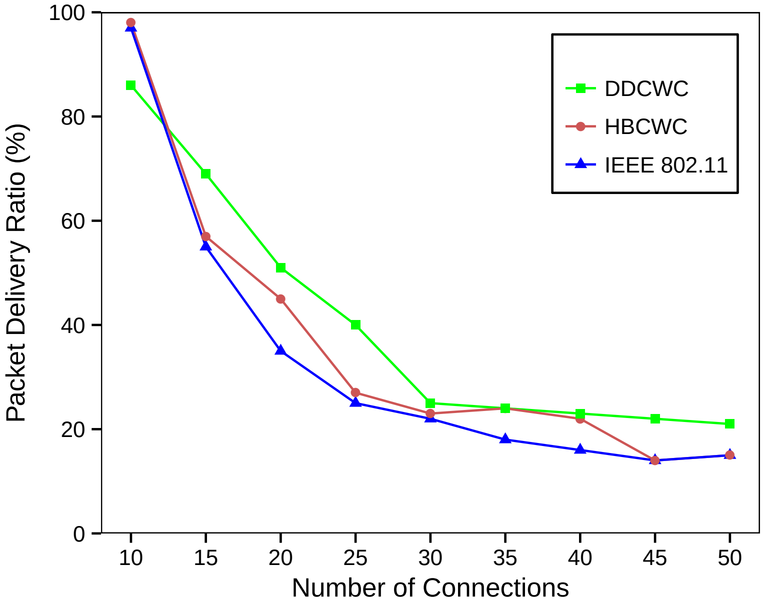


Figure 3.2: The packet delivery ratio (PDR).

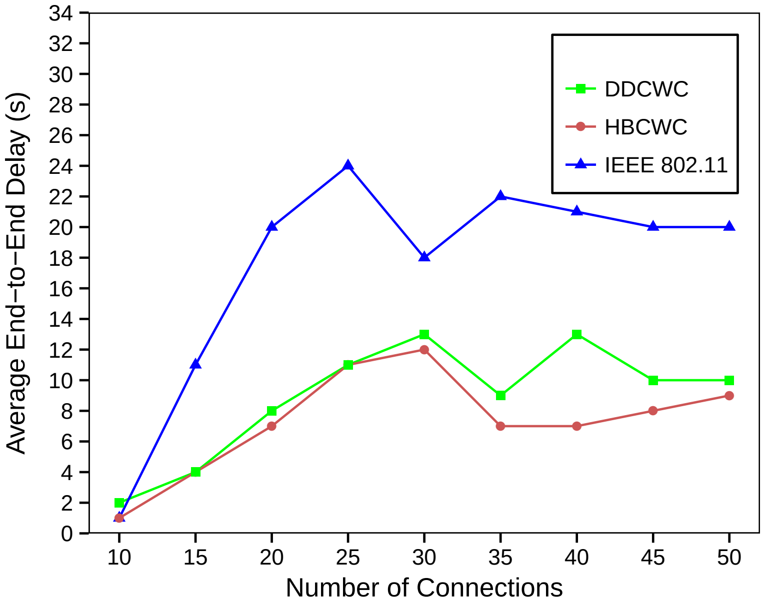


Figure 3.3: The average end-to-end delay.

Previously, we compared our new MAC protocols which propose new backoff control mechanisms against the IEEE 802.11 standard, which uses BEB mechanism. We now compare our protocols against other non-standard solutions to demonstrate that our protocols are achieve significant performance improvements. The proposed algorithms, HBCWC and DDCWC, offer very simple and similar modifications (i.e. similar overhead or simplicity) to algorithms such as MILD, DIDD, and EIED, as explained in Section 2.1.4; therefore, they are used for comparison against our protocols. In addition, the LMILD algorithm, which also increases the contention window value in any node overhearing a collision, is also selected. It is noteworthy that other solutions studied in Section 2.1.4 were not selected since they introduce more overhead, such as computational overhead.

Figure 3.4 compares the average end-to-end delay for all selected mechanisms. This figure shows the impact of adjusting CW_{min} on the average end-to-end delay. It shows that, by increasing CW_{min}, it causes the average end-to-end delay for IEEE 802.11 be decrease. Figure 3.4 also shows that the MILD scheme has the highest, and DDCWC has the lowest end-to-end delay. MILD has the highest result because it decreases the backoff ranges by one unit, which means that it requires a longer time to adapt itself when facing variable network conditions. Furthermore, DIDD shows better results than other methods, except for our own, since it gently and gradually decreases CW values after a successful packet transmission. Our proposed solutions achieve better performance compared to others by taking network conditions into account. In addition, DDCWC has the best average end-to-end delay since it has more important factors such as assigning different backoff ranges based on channel history, and decreasing CW values more gradually than HBCWC.

In Figure 3.5, we present the average packet delivery ratio for different methods. The BEB mechanism, which is used by IEEE 802.11 for adjusting the backoff ranges, shows increases in the average PDR by increasing the CW_{min}. All solutions except LMILD have better average PDR compared to the BEB mechanism. DDCWC achieves better results since it is able to adapt the backoff range according to network conditions by dividing the backoff range into different small sub-ranges, which helps at decreasing the number of collisions.

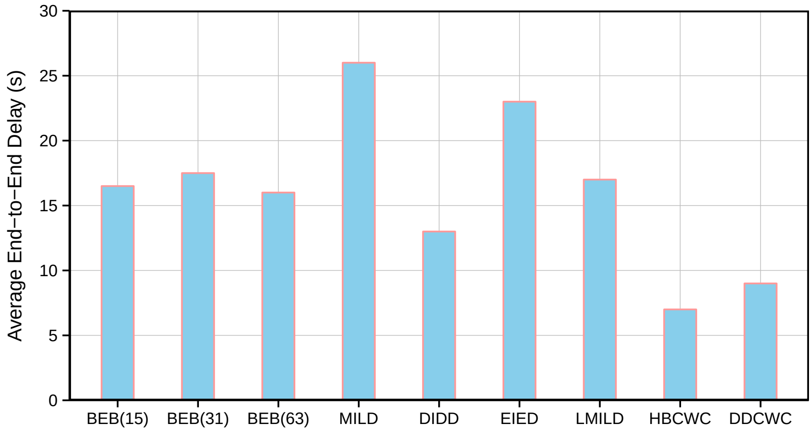


Figure 3.4: The average end-to-end delay.

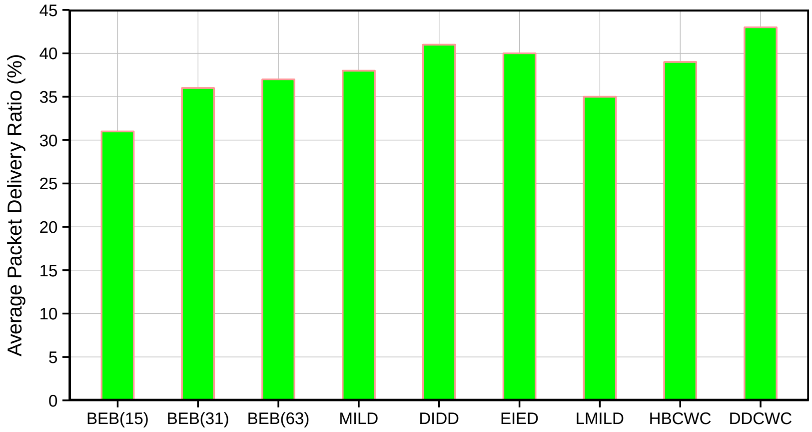


Figure 3.5: The average packet delivery ratio (PDR).

3.4.2 Simulation Settings and Results for DBM-ACW

To evaluate the performance of DBM-ACW in comparison with IEEE 802.11p and HBCWC in vehicular environments, we used OMNeT++ (version 4.2.2) coupled with the INETMANET framework for network simulation; SUMO is also used in order to provide a realistic vehicular scenario.

In order to study the efficiency of DBM-ACW, we evaluate its performance in both highway and urban scenarios. The general simulation parameters are as follows: each vehicle generates constant bit rate traffic using User Datagram Protocol (UDP) datagrams. We chose UDP and not TCP for the reasons stated as follows [CWH07]: (a) TCP scales back its transmission window to compensate for congested packets, which is in contradiction with our goal of checking how throughput is affected by the wireless propagation characteristics of the channel; and (b) TCP uses an Automatic Repeat reQuest (ARQ) mechanism to retransmit lost packets which pauses transmission of other packets, and it impacts the performance of normal packets which again is not our goal. 512-byte datagrams were transmitted at a rate of 4 packets per second.

Considering the routing protocol, we assessed different routing protocols (i.e., AODV, OLSR, DYMO, DSR) and, despite of the different overall performance levels obtained by these protocols, they have the same impact on the different MAC protocols evaluated in this section. Thus, the results presented refer to the AODV routing protocol; notice that, since several researchers use this protocol as well, it allows making comparisons against other proposals easier. To accurately model real world conditions, we used the radio propagation model presented in [BCCM12]. The transmission range was set to 250 m (-85 dBm), and the interference range is up to 4 km (-110 dBm) [Eic07]. Table 3.4 summarizes the simulation parameters.

Table 3.4: The simulation parameters.

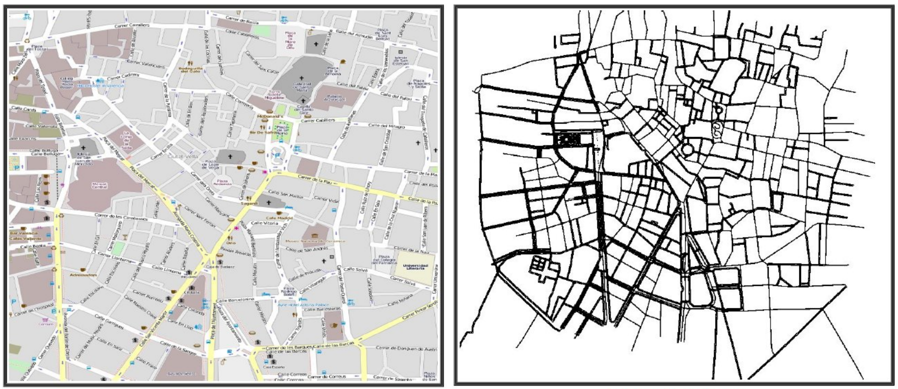
Simulation Parameter	**Value**
Traffic type	CBR
CBR packet size	512 byte
CBR data rate	4 packet/s
Transport protocol	UDP
Routing protocol	AODV
Max. and Min. of CW	7, 1023
Max. number of retransmissions	7
Max. queue size	14
RTS/CTS threshold	2346 byte
Slot time	13 μs
Simulation time	300 seconds
Number of repetitions	10

The metrics used to evaluate the performance of the MAC solutions in Section 3.4.1 are still used for this study. Moreover, new metrics will be used in this section as follows: (a) Standard Deviation of end-to-end delay, which shows how much variation exists from the average end-to-end delay; and (b) average MAC collisions, which shows the average number of collisions experienced per source.

In order to evaluate the protocols in vehicular ad hoc networks, two common scenarios that come to mind are highway, and urban scenarios. While the traffic is homogeneous in one-dimensional highway scenarios, urban scenarios show a two-dimensional traffic pattern, which is more complex and challenging.

3.4.2.1 Urban Scenarios

In contrast to highway scenarios, where vehicles always drive in a same direction, and where obstacles are mostly non existent, urban scenarios offer more flexibility in terms of mobility, but also introduce more obstacles like buildings, vehicles, urban furniture, etc [BLJL10, MFT$^+$13, SEGD11]. This issue leads to lower transmission ranges for urban scenarios. As described in Section 3.4.2, we used SUMO and connected it to OMNeT++ in order to generate realistic urban mobility traces. The urban scenario represents an area of $1,500 \times 1,500$ m^2 that is extracted from the downtown area of Valencia (Spain) by using digital maps freely available in OpenStreetMap, and including real obstacles. Figure 3.6 shows two map views: the OpenStreetMap view and the SUMO view.



OpenStreetMap View

SUMO View

Figure 3.6: Valencia real urban scenario.

The vehicle and mobility generation are handled by SUMO. However, when a vehicle reaches its destination in SUMO, it must leave the simulation, and so we cannot ensure a constant number of vehicles throughout the entire simulation time. Therefore, the VACaMobil tool by [BTT$^+$13] is used to handle this issue, inserting new vehicles in the simulation when other vehicles leave it, thereby maintaining the same number of vehicles throughout the simulation time. In our experiments, the number of nodes varies from 50 to 200.

In this first experiment, we evaluate DBM-ACW in an urban scenario using V2V communications. Since we are interested in highly congested environments, we define a large number of connections, so that each vehicle, immediately after joining the network, starts a new connection and maintains it active until the destination leaves the network. When this occurs, a new destination will be chosen by the transmitter. This experiment represents a stressing situation for a MAC protocol due to the large number of simultaneous connections. Thus, the experimental setup is adequate to assess how DBM-ACW is able to overcome a high number of collisions to obtain a suitable throughput.

Figure 3.7 shows the PDR for DBM-ACW when varying the number of source nodes. This figure shows that DBM-ACW outperforms both IEEE 802.11p and HBCWC. We can observe that the improvement ratio in high density networks (more than 100 nodes) is higher than for low density networks. This stems from the fact that DBM-ACW avoids resetting the CW to the minimum value, and it mostly maintains the average CW size at high values in the presence of frequent collisions. Therefore, it is able to decrease the number of dropped packets but, under low densities, when the collision frequency is low, the degree of efficiency is not comparable to high density situations. Also, HBCWC shows a good performance because it also estimates the network density to choose the optimal CW size. However, the results show that resetting the CW size upon a successful transmission, like 802.11p does, has a significant cost in terms of PDR.

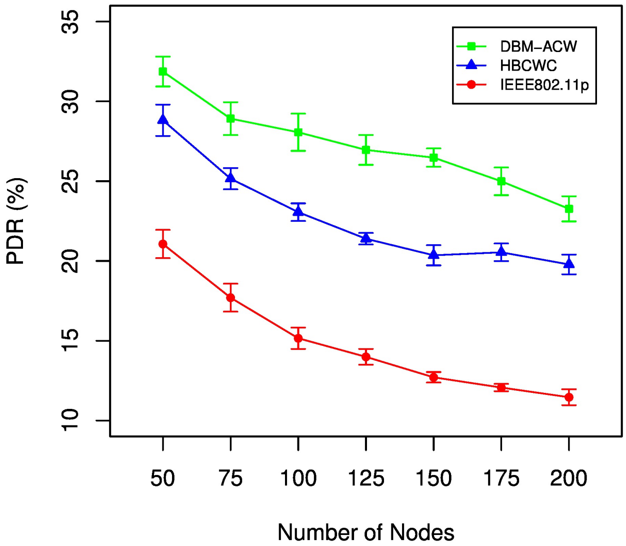


Figure 3.7: PDR for the urban scenario.

The average number of MAC collisions, shown in Figure 3.8, offers a hint on how to achieve improvements in terms of PDR. As can be observed in this figure, DBM-ACW shows that the optimal CW was chosen so that it decreases the probability of picking the same backoff value, and consequently the number of collisions.

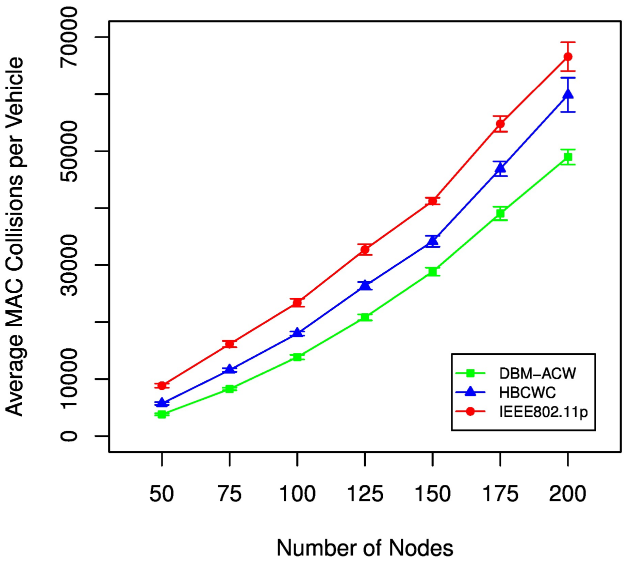


Figure 3.8: Average number of collisions for the urban scenario.

One of the key differences between IEEE 802.11p and our approach is that 802.11p resets the CW size to the minimum value when the retransmission limit is reached, without taking into account that this event is possibly associated to channel collisions; thus, it assigns a minimum CW size for the next packet. Considering this behaviour, one can expect that the new packet will have less chance of success in order to be sent, and will also need more retransmissions on average. Therefore, our approach achieves lower end-to-end delay than the IEEE 802.11p standard, as shown in Figure 3.9.

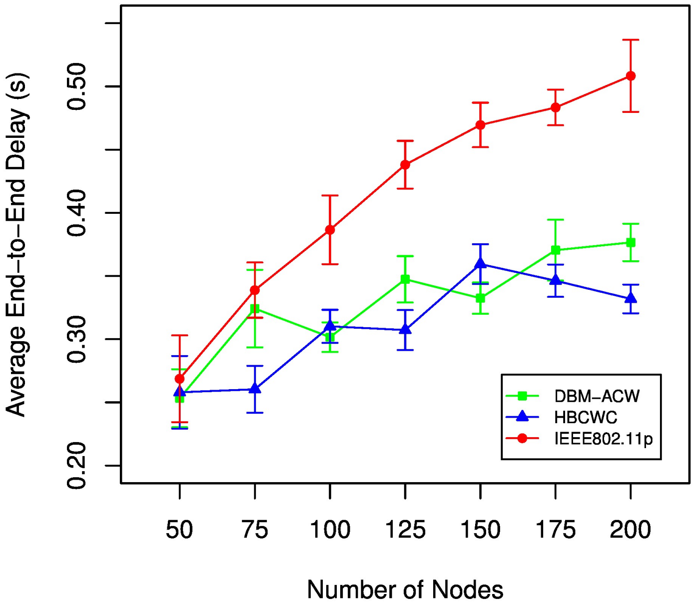


Figure 3.9: Average end-to-end delay for the urban scenario.

Figure 3.9 evidences the difference between our approach and HBCWC, which is further clarified in Table 3.5. In particular, we avoid resetting the CW size for the case in which we observed two consecutive successful transmissions before detecting an unsuccessful transmission. As a result, we are able to achieve improvements in terms of end-to-end delay, as well as an improved standard deviation for delay when comparing DBM-ACW with HBCWC. In HBCWC, few packets are sent with very low delay, and this issue decreases the total end-to-end delay, while in DBM-ACW most of the packets have delays close to the average value.

Moreover, as shown in Figure 3.9, end-to-end delay under high densities does not follow the same trend as 802.11p does, showing a higher bound for delay so that, as the network density increases, the average end-to-end delay remains low, fluctuating at values close to 0.35 seconds. Therefore, we find that DBM-ACW improves IEEE 802.11p scalability, which represents an important challenge in vehicular ad hoc networks.

Table 3.5: Standard deviation of delays for the urban scenario.

	50	**75**	**100**	**125**	**150**	**175**	**200**
DBM-ACW	0.42	0.45	0.46	0.47	0.49	0.52	0.53
HBCWC	0.44	0.44	0.48	0.50	0.55	0.54	0.53

Overall, our approach improves the PDR by 47%, and the end-to-end delay by 16% when compared with IEEE 802.11p, while also improving the PDR by 16% in comparison with HBCWC.

3.4.2.2 Highway Scenarios

The highway scenario models a 4 km highway with 3 lanes, where the lane width is 3 m. As assumed in the previous section, the destination is randomly chosen, so it can be a car ahead or behind of the transmitter. In order to model a realistic scenario, we assumed that vehicles can be selected based on a normal distribution from three different categories that are summarized in Table 4.3. Sigma models the driver's imperfection, which is selected in the range from zero to one. The driver's imperfection shows the differences between the real speed and the desired speed. Moreover, vehicles are injected in the highway according to a Poisson process with a mean interval time of 2 seconds, and where the best lane is assigned to each vehicle. In contrast to the urban scenario, the transmission rate is 2 packets per second. In each graph, the probability of sending a message defines the transmission probability for each vehicle throughout the simulation.

A comparison of these results with the results for the urban environment shows that both of highway and urban scenarios follow the same trends, as pointed out by [WWM07]. In the assumed highway scenario, the number of collisions is lower than in the urban scenario (due to the lower transmission rate), depicted in Figure 3.11. This figure shows that DBM-ACW improves the number of collisions, but the trend is not exactly the same as for the urban scenario, meaning that, for lower densities, DBM-ACW's performance is similar to HBCWC. Consequently, DBM-ACW cannot achieve a high improvement ratio compared with HBCWC in terms of PDR under lower densities, as depicted in Figure 3.10. However, for high densities, DBM-ACW achieves a higher improvement ratio compared to HBCWC when simultaneously considering both the PDR and the number of collisions. Also notice that, despite DBM-ACW shows a lower improvement ratio when compared with the urban scenario, it still shows better results than HBCWC and IEEE 802.11p considering the PDR and the number of collisions.

Table 3.6: The vehicle types.

Vehicle Type	**Accel.** (ms^{-2})	**Decel.** (ms^{-2})	**Sigma**	**Max Speed** (ms^{-1})	**Probability** (%)
Fast	4	6	0.2	36	10
Normal	2	4	0.3	28	80
Slow	2	4	0.5	20	10

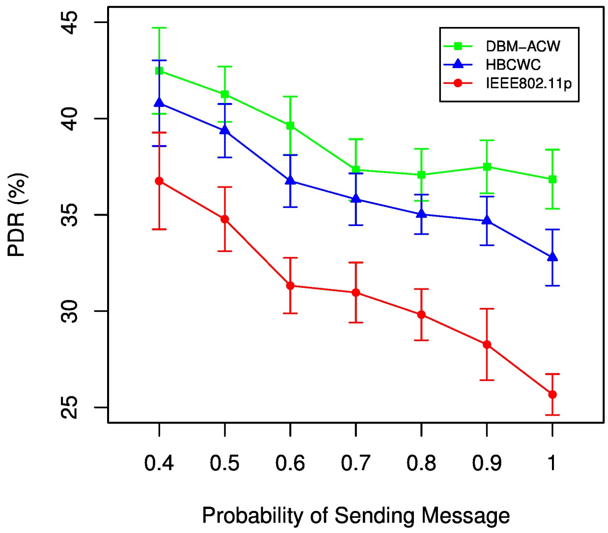


Figure 3.10: PDR for the highway scenario.

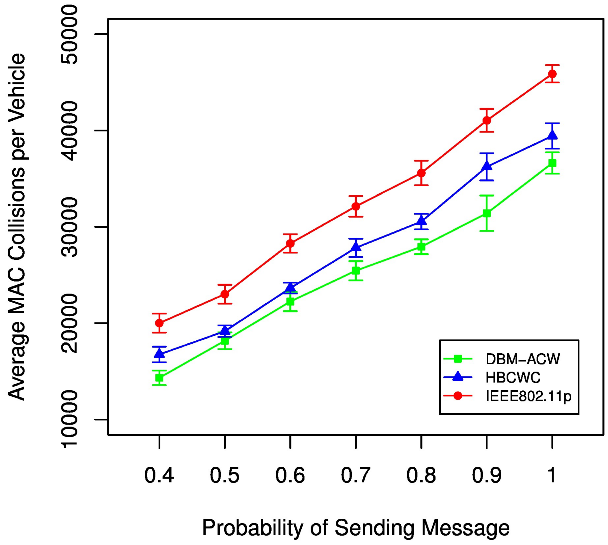


Figure 3.11: Average number of collisions for the highway scenario.

In terms of end-to-end delay, DBM-ACW clearly outperforms IEEE 802.11p, as shown in Figure 3.12. Also, while IEEE 802.11p has an increasing trend, DBM-ACW shows a decreasing trend, meaning that our approach does not increase the delay when the number of connections increases, as desired.

Figure 3.12 shows that HBCWC achieves a slightly better delay when compared with DBM-ACW. However, DBM-ACW achieves a better trade-off between PDR and end-to-end delay, meaning that the total PDR improvement ratio is higher than the delay degradation ratio when compared with HBCWC.

Overall, we obtain a 20% improvement in terms of PDR, and a 22% improvement in terms of end-to-end delay compared with IEEE 802.11p, as well as a 7% improvement in PDR compared with HBCWC.

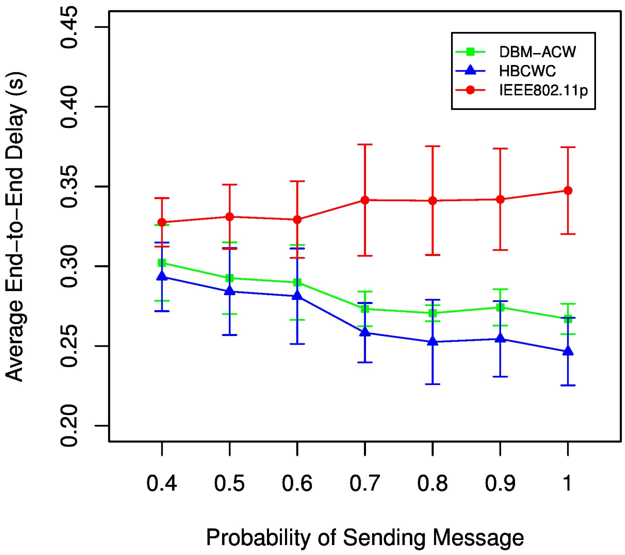


Figure 3.12: Average end-to-end delay for the highway scenario.

3.5 Conclusions

In this chapter we presented several new solutions to improve the performance of IEEE 802.11 and 802.11p for different types of ad hoc networks. We started by presenting two different methods, HBCWC and DDCWC, in order to optimally adjust the backoff ranges for the different nodes of a MANET, thereby decreasing the number of collisions and improving the average end-to-end delay for unicast applications. In order to evaluate the performance of our proposals we simulated a common ad hoc scenario where randomly generated nodes move inside the simulation environment.

We compared them against the available standard for mobile ad hoc networks, IEEE 802.11, noticing that both of our proposals achieve better results in terms of average number of collisions, packet delivery ratio, and average end-to-end delay. In detail, DDCWC achieves better packet delivery ratio, while HBCWC achieves lower end-to-end delays. Moreover, we compared our two methods against other proposals in this field, and the results showed that our methods outperform the state of the art.

We also proposed a new enhanced version of the IEEE 802.11p MAC protocol, DBM-ACW, in order to provide a better support for unicast applications in vehicular ad hoc networks. In order to assess the effectiveness of DBM-ACW, we evaluated our proposal in typical vehicular scenarios such as highway and urban scenarios. Simulation results showed that our solution achieves better performance on both selected scenarios in terms of average number of collisions, packet delivery ratio, and average end-to-end delay. Furthermore, we compared DBM-ACW with our previously proposed solutions, HBCWC, in vehicular environments.

Chapter 4

Token-Based MAC Protocol for VANETs

4.1 Introduction

In this chapter we present our Dynamic Token Based MAC (DTB-MAC) protocol, a novel solution targeting vehicular environments that combines the token passing concept with a random access MAC protocol in order to support an efficient exchange of beacon messages for traffic safety applications. We explain in detail our proposed method, and then proceed by evaluating the performance of DTB-MAC against the available standard through computer simulations in different situations, including both highway and urban scenarios. We conclude this chapter by showing that DTB-MAC achieves better performance, providing timely and reliable inter-vehicle communication for traffic safety applications compared to the IEEE 802.11p MAC.

4.2 Dynamic Token-Based MAC Protocol

We consider a vehicular environment with vehicles (the term “vehicle” and “node” are used interchangeably throughout this chapter) which pertain to one or more virtual rings, as shown in Figure 4.1. We introduce the concept of “virtual rings”, which are rings created between vehicles in the same neighbourhood that are dynamically defined based on the vehicle mobility. Each node starts as an individual entity, and it transmits its beacon without cooperating with its surrounding environment. Upon the first beacon reception, a node is notified about the existence of other nearby nodes and tries to join available rings in its neighbourhood. All the nodes interested in joining a ring compete with other nodes through a random access MAC protocol. The main benefit of this strategy is that, after joining a ring, nodes no longer need to compete with each other to gain channel access, except in those cases where the token is lost.

Within the ring, only the node holding the token can transmit a frame (in our case a beacon) on the channel. The term "token" refers to a privilege which is given to a ring member when it is chosen by another ring member to be the next beacon transmitter. Notice that DTB-MAC does not require any extra packet transmission for token passing, being that nodes are notified about the next transmitter only by listening to the beacon transmission since a piggybacking approach is adopted. While the token is circulating in a ring, nodes can find their turns to access the channel based on data embedded in beacons. In particular, the token holder selects another ring member as the next token holder, and includes that information in the beacon being transmitted. If the token is lost for any reason, our solution relies on a random access MAC method in order to find a new transmitter and inject a new token into the ring, thereby keeping it alive. It is important to highlight that, by keeping the token circulating in the ring as much as possible, DTB-MAC is able to provide improved performance. Throughout this chapter, we use several symbols in order to explain our methods, as summarized in Table 4.1.

Table 4.1: Summary of symbols used along this chapter.

Symbol	**Definition**
THN	token holder node
BTHN	backup token holder node
RMN	ring member node
DN	dissociative node
SDN	semi-dissociative node
t_{DN}	waiting time for DN to transmit a beacon
t_{THN}	waiting time for THN to transmit a beacon
t_{BTHN}	waiting time for BTHN to transmit a beacon
t_{old}	timeout for an old neighbouring list entries
p_{RMN}	probability for one RMN to transmit
t_{join}	time period after which a THN sends a frame if SDNs do not transmit
t_{rem}	remaining time until the next beacon generation
C	random number between 0 and t_{rem}
t_{DIFF}	dynamic time period which is calculated based on C and Q

Figure 4.1 shows an illustrative example of the virtual ring. As can be observed vehicles can be in the following states:

- **Token Holder Node (THN)**: a node which is allowed to transmit.
- **Backup Token Holder Node (BTHN)**: a node which is allowed to transmit if the THN node fails to transmit.
- **Ring Member Node (RMN)**: a node which is in a ring but cannot transmit since it does not hold the token.
- **Dissociative Node (DN)**: a node which does not belong to any ring and is not part of a ring joining procedure either.
- **Semi-Dissociative Node (SDN)**: a node which does not belong to any ring, but is attempting to join a ring following a beacon reception.

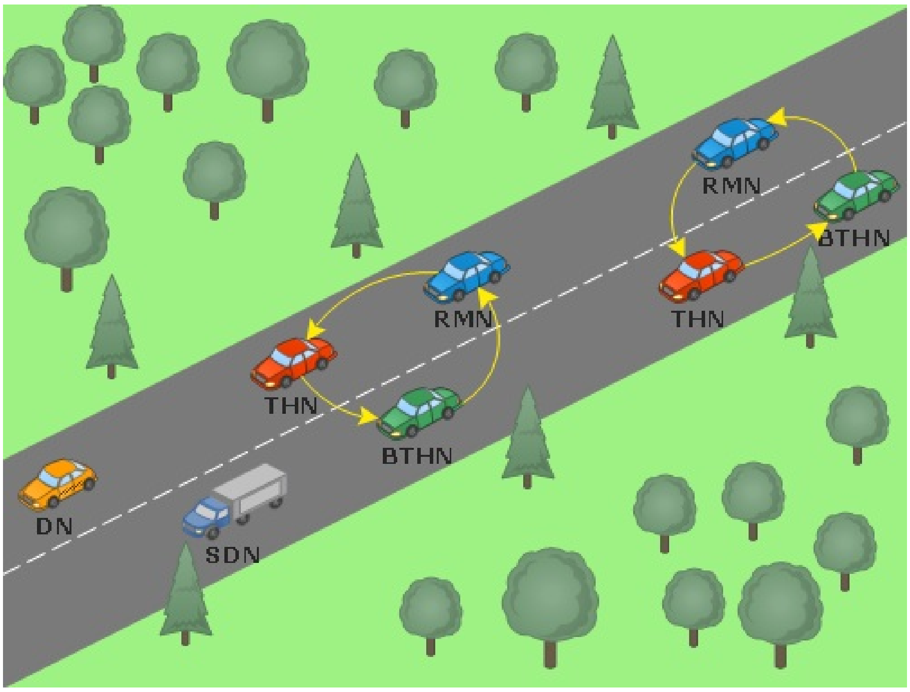


Figure 4.1: An illustrative example of the virtual ring in a highway scenario.

Figure 4.2 illustrates the transitions between these different states in the scope of our proposal. As the figure shows, vehicles are in DN or SDN states before joining a ring, and they must compete to get access to the channel and join a ring. After finishing the joining process, the state of vehicles including RMN, BTHN, and THN while they belong to a ring, and they have to wait for the token to transmit their beacons. The key processes involved in the state transitions are described in more detail below.

4.2.1 Joining Process

Joining a ring is always an issue for token-based MAC protocols which are designed for dynamic wireless networks, especially in highly mobile VANET environments. The complexity stems from the collision probability between the ring members and new nodes attempting to join the ring. The top part of Figure 4.2 shows the joining process in DTB-MAC; notice that each vehicle starts from the DN state. If no beacons are received, it remains in that state, meaning that it will belong to a single-node ring and generate its own beacons. Upon a beacon reception from neighbouring nodes, the node switches to the SDN state.

When we have more than one SDN node in the neighbourhood, these nodes will compete with each other in order to join the ring by sending their own beacon,

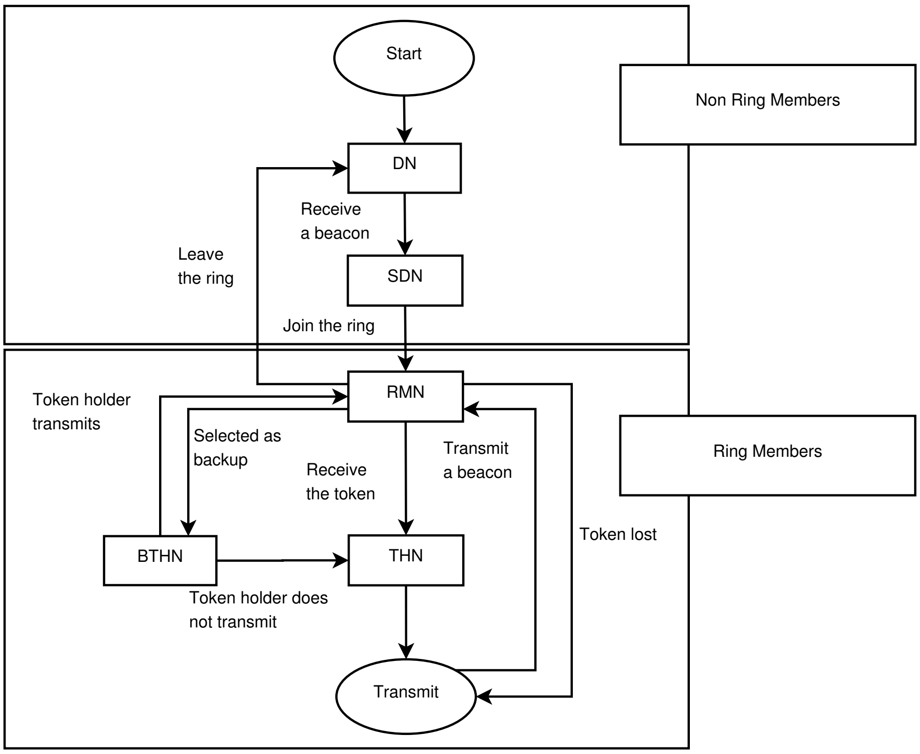


Figure 4.2: State transition diagram of DTB-MAC.

meaning that there is a potential for collisions to occur. To reduce this problem, the nodes in the SDN state must wait for a predefined time period (t_{THN}), plus a dynamic time period ($t_{DIFF} \geq 0$) before sending their beacons. A token holder chooses to transmit or to allow an SDN node to join a ring after time period t_{THN}. Therefore, SDN nodes must wait at least t_{THN} after a beacon reception in order to avoid colliding with the scheduled ring transmission. Also, by waiting for a t_{DIFF} period, DTB-MAC, decreases the probability of collision occurrence among SDN nodes. The value of t_{DIFF} is dynamically calculated based on the remaining time until the next beacon generation (t_{rem}) according to the following expression:

$$t_{DIFF} = \alpha \times C \tag{4.1}$$

where C is a random number of time slots between 0 and t_{rem}, and α is a value between 0 and 1 that allows fine tuning the behavior of our protocol in order to keep the DTB-MAC delay low. As we increase the value of α, it decreases the number of collisions between SDN nodes. However, bigger α values decrease the probability of joining a ring. Therefore, α must provide a balance between the probability of joining the ring and the number of collisions among SDN nodes. Moreover, t_{DIFF} decreases with decreasing t_{rem} values. Whenever an SDN node finds the channel idle and transmits a beacon, it switches to the RMN state. As a result, the probability of collision occurrence decreases, although it cannot be reduced to zero.

4.2.2 Ring Management

The highly dynamic topology typical of vehicular environments makes the creation of fixed clusters difficult and undesirable; the same applies to selecting one of the ring members as a coordinator. Therefore, the VANET research community looks for decentralized methods in order to decrease the overhead associated to central element selection processes.

DTB-MAC does not need any coordinator to manage internal ring competition for accessing the channel. Each node is responsible of keeping the token circulating inside the ring. Before explaining how DTB-MAC manages the token passing, we define the frame header format in both IEEE 802.11p and DTB-MAC protocols.

Figure 4.3 introduces the header format of the IEEE 802.11p and DTB-MAC protocols. The header used by DTB-MAC is an extension of IEEE 802.11p with some extra information. As can be seen in the figure, we only add one new field, t_{rem}, which includes the remaining time before the next beacon generation. Address 3 and Address 4 fields are used in order to identify the token holder and the backup token holder nodes, respectively. The remaining fields have the same usage as in the IEEE 802.11p standard.

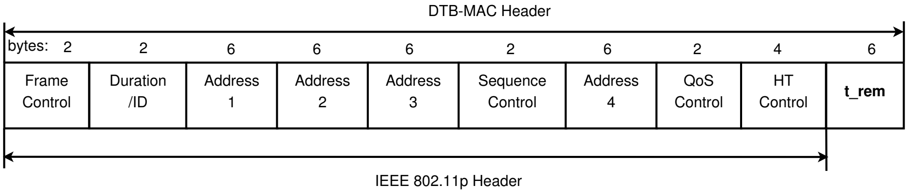


Figure 4.3: IEEE 802.11p and DTB-MAC header format.

In order to maintain the token, ring members have three responsibilities:

- **Making a list of ring members**

  In order to grant another node in the ring the permission to transmit, each node must make a neighbour list based on data retrieved from the beacons received. Whenever a node receives a new beacon, it saves the source address and the t_{rem} of the beacon source in the neighbouring list. This means that the neighbouring list is updated following every beacon reception. If a record related to the source node already exists in the list, only the t_{rem} value is updated. Otherwise, a new record is created for the source node.

- **Selecting next token holders**

  Before each beacon transmission, a node must select two nodes from its neighbour list as the next token and backup token holder, and also measure its own t_{rem}. This information is included in the beacon and broadcasted. Therefore, the neighbouring nodes can decide whether to send (THN) or wait (RMN and BTHN) based on the information received. THN and BTHN are selected based on t_{rem}, meaning that each node selects two nodes from its neighbouring list with the lowest t_{rem}. This mechanism assigns a higher priority to those nodes with lower t_{rem} in order to allow them to send their own beacons before reaching the deadline. We need to mention that expired beacons are dropped. Therefore, DTB-MAC will always have, at most, one safety message to transmit.

- **Recovering from a lost token**

  Ring members which are not selected as token holders or backup token holders check the channel during a predefined time period t_{BTHN} (waiting for selected token and backup token holder transmissions). If they cannot detect any activity in the channel during this period, it means that a token loss has occurred. This situation can be due to a problem in the previous beacon reception, causing the selected nodes to miss their THN/BTHN status notification. Also, it can occur that they do not have any beacon in their queues to transmit at the time they receive the beacon. To solve this problem, and to regenerate the token, ring members wait for a time period equal to t_{DIFF}, as calculated in Equation 4.1. Then, the ring member choosing the smallest t_{DIFF} value transmits, and selects the next token holder.

4.2.3 Ring Operation

There are three possibilities for a ring member to transmit a beacon, as shown in the bottom part of Figure 4.2.

First, if a node is selected as the token holder, it switches to the THN state, and, following the beacon reception, the node chooses to transmit its own beacon with a probability p_{RMN}, after a time period t_{THN}. If it chooses not to send a beacon after t_{THN}, it delays the transmission for a predefined time period (t_{join}), and then transmits only if it finds the channel idle (a new node does not join the ring). Second, if it is selected as a backup token holder, it changes its state to BTHN, and it transmits if it finds the channel idle for one slot time after time period t_{BTHN}. BTHN is calculated according to the following expression:

$$t_{BTHN} = t_{THN} + t_{join} \tag{4.2}$$

The third case happens after a token loss, so that the selected nodes (THN or BTHN) do not transmit. In that case, other ring members have the opportunity to transmit instead. If a node is not selected, it checks the channel during a t_{BTHN} time period after the beacon reception (waiting for the selected token or backup token holder transmission). If it cannot detect any activity in the channel during this period, it waits for a time period equal to t_{DIFF}, as calculated in Equation 4.1. Then, if it can find the channel free, it transmits and regenerates the token. The use of a dynamic waiting time period equal to t_{DIFF} causes a reduction on the number of collisions between RMN nodes. After transmission, each node goes back to the RMN state and waits until it again obtains permission to transmit. Figure 4.4 illustrates the transmission order of the different nodes.

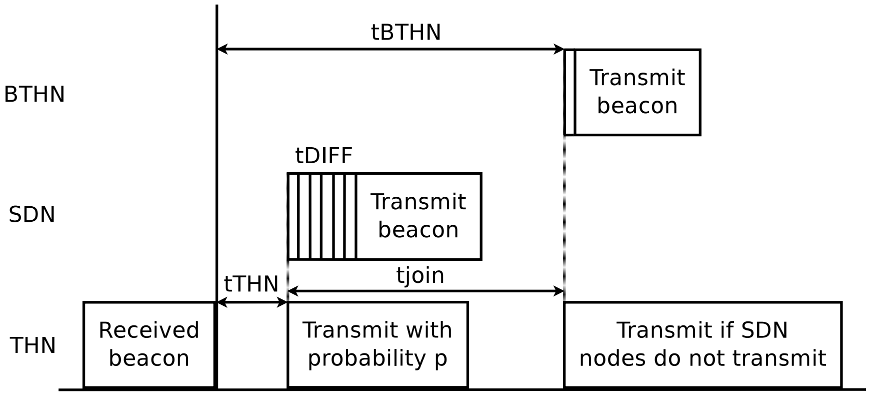


Figure 4.4: Transmission scheduling in DTB-MAC.

4.2.4 Ring Refresh Process

If ring members do not remove old entries, they could select nodes which are no longer in their neighbourhood. This situation would increase the delay and degrade the efficiency of our DTB-MAC protocol, thus being clearly undesirable. To avoid this, ring members remove old entries, meaning that each node removes the nodes from its neighbouring list if it fails to receive any beacons from them during a predefined time period (t_{old}). This value was chosen based on topology change speed. If the topology changes very fast, the chosen value should be smaller in order to detect nodes leaving a ring as soon as possible. In this chapter, we chose an optimised static parameter for the selected simulation scenario environment. However, for future works, it should be dynamically chosen based on node mobility levels to obtain the best performance in different network scenarios.

4.3 Performance Evaluation

To assess the effectiveness of the proposed DTB-MAC protocol we rely on simulation. In this section, we describe the simulation details, including simulation scenario parameters and the protocol configurations.

4.3.1 Simulation Settings

For highway simulation, we consider a highway with 2.2 km in length and 2 lanes, where the width of each lane is 3 m. We used SUMO in order to generate realistic vehicular mobility. Traffic density varies from 16 to 43 cars per lane per km. We assumed that, for each vehicle, parameters such as acceleration (m/s^2), deceleration (m/s^2), and maximum speed (m/s) are set to 2, 4, and 50, respectively.

For urban simulation, the selected scenario represents an area of $2.6km \times 2.6km$ that is extracted by using digital maps freely available in OpenStreetMap from the downtown of Milan, which has a typical structure of an old European city, and including real obstacles, as shown in Figure 4.5. The vehicle and mobility generation is handled by SUMO. In addition, similarly to the previous chapter, we selected the VACaMobil tool to maintain a same number of vehicles throughout the simulation. In our urban scenario, traffic density varies from 5 to 80 vehicles per square km. We implemented our proposed MAC protocol in OMNeT++ (version 4.4.1), and used the IEEE 802.11p implementation made available by the Veins framework (version 2.1) for OMNeT++.

Figure 4.5: Map used for urban simulations ($2.6 \times 2.6km$).

Each beacon includes a 500 byte payload, and it is generated every 0.1 seconds. Also, it is transmitted with a data rate of 6 Mbps within a transmission range of 500 m. In order to present a more realistic vehicular environment, we used the radio propagation model made available by Veins for VANET communications [SED13]. We run the simulation for 280 seconds, although results are only captured after 250 seconds to allow the system to reach a steady state. The beacon priority and the CW values when broadcasting are AC[0], and 15, respectively. Table 4.2 summarizes the simulation parameters.

Table 4.2: The simulation parameters.

Simulation Parameters	Value
Highway Length	2200 m
Number of lanes	2
Urban scenario	an area of $2.6km \times 2.6km$ from the downtown of Milan
Density for highway scenario	16-43 vehicles/lane/km
Density for urban scenario	5-80 vehicles/km^2
Transmission Range	500 m
Propagation model	Sommer et. al obstacle based model with Shadowing + Nakagami small scale fading
Beacon frequency	1, 5 and 10 Hz
Packet length	500 bytes
Frequency	5.9 GHZ
Data Rate	6 Mbps
Beacon Priority	AC[0]
Broadcasting CW	15
Warm-up time	250 s
Simulation time	280 s

Table 4.3 shows the parameters used by the DTB-MAC protocol. These parameter values were chosen based on extensive simulations where different combinations of values were evaluated to obtain the best performance in the selected simulation scenario. t_{THN} was obtained so that each beacon is received by all neighbouring nodes before a new beacon transmission. Also, t_{join} is defined based on the average time period where nodes can join a new ring.

Table 4.3: DTB-MAC protocol parameters.

Parameter	Value
t_{DN}	0.9 s
t_{THN}	0.25 ms
t_{old}	0.1 s
t_{join}	3 ms
α	0.1

According to [SL13], we chose widely used performance metrics to evaluate the performance of the proposed scheme: (a) Beacon Delivery Ratio (BDR), which is defined as the ratio between the number of beacons successfully received by nodes in the transmission range and the number of beacons transmitted; (b) average number of MAC collisions per second, which shows the average number of collisions experienced per second; (c) dropped beacon ratio, which is calculated as the number of beacons that are dropped (because the beacon transmission deadline expires) to the total number of beacons; and (d) channel utilization, which shows the amount of time that the channel is used for successful and failed transmissions, along with the idle time.

4.3.2 Simulation Results and Analysis

To show that our proposed protocol is able to improve performance, we choose different scenarios including highway and urban scenarios. In each scenario, we compare the DTB-MAC and the IEEE 802.11p protocols in terms of beacon delivery ratio, average number of collisions, and channel utilization under different network densities. In this chapter, the beacon frequency is equal to 10 Hz when it is not mentioned.

4.3.2.1 Highway Scenario

Figure 4.6 shows the results for different network densities. For the beacon delivery ratio calculation, we assumed zero delivery ratio for dropped packets. We noticed that, as expected, DTB-MAC increases the beacon delivery ratio for different network densities by decreasing the number of channel contentions. Since DTB-MAC can perfectly circulate the token between ring members, it can prevent collision occurrence. As can be seen, DTB-MAC achieves more improvements in higher than lower network densities. The reason is that, for lower densities, the number of nodes in each neighbourhood is low, which increases the probability of choosing a neighbour node without a beacon ready for transmission. This issue provokes a lot of failures in the token passing procedure, causing DTB-MAC to switch to the random access MAC protocol. Therefore, the amount of improvement that DTB-MAC achieves at low densities differs from the high density case. In this way, DTB-MAC can solve the problem of TDMA-based techniques by providing a good beacon delivery ratio in high density networks, while it can also show improvements compared to IEEE 802.11p in low density networks.

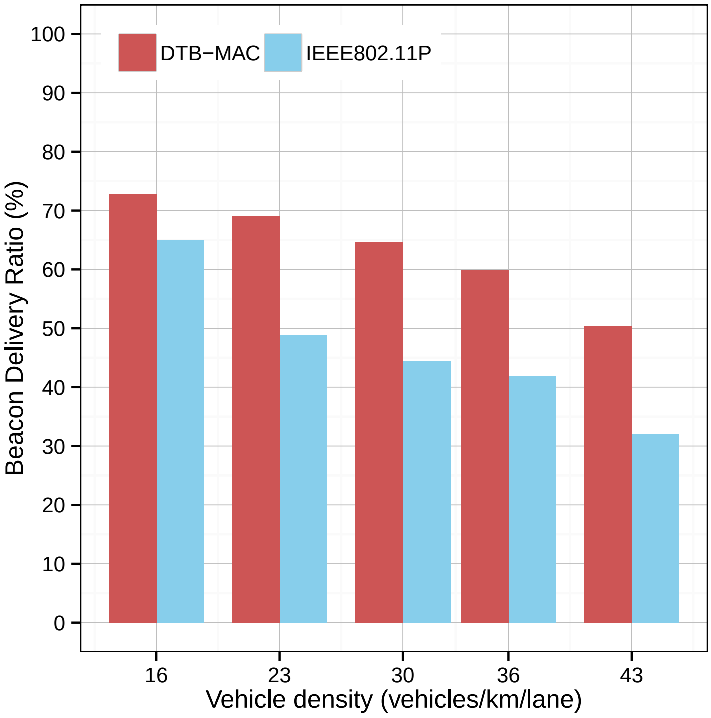


Figure 4.6: Beacon delivery ratio for the highway scenario.

To better understand how DTB-MAC is able to achieve higher beacon delivery ratios, in Figure 4.7 we present the average number of collisions per second for both DTB-MAC and IEEE 802.11p. This figure shows that, at low densities, DTB-MAC is not so effective at preventing collisions as at high densities. These results stem from the fact that DTB-MAC relies on a random access protocol at low densities, while at high densities DTB-MAC relies on token passing instead. In the latter case, the token circulates faster and with lower loss probability since a large number of nodes is waiting for the token, and have beacons ready to transmit.

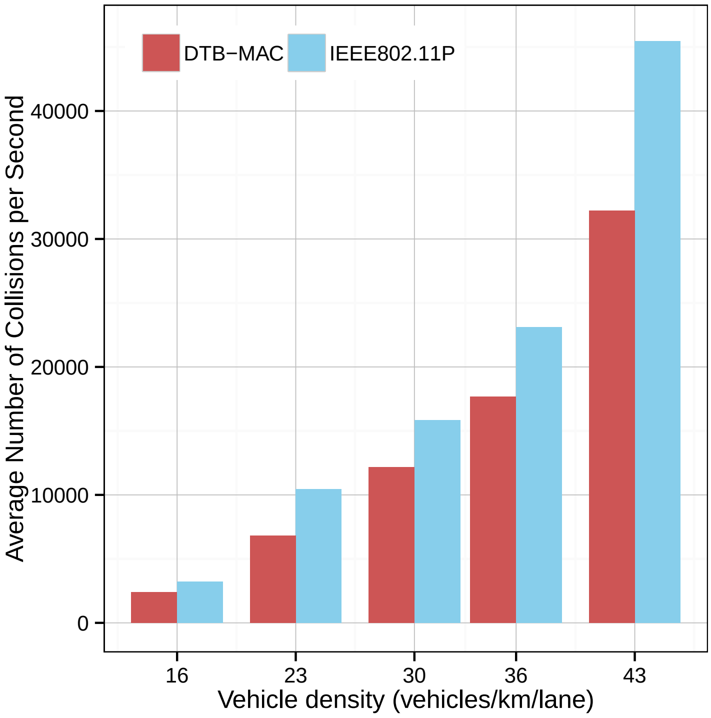


Figure 4.7: Average number of collisions per second for the highway scenario.

One of the token passing characteristics, which is expected to be a problem when attempting to provide efficient communication solutions in vehicular environments, is the time period that each node has to wait to receive the token. With respect to the strict delay limit of safety communications, the waiting time can cause a large number of packet drops. However, the dropped beacon ratio results shown in Figure 4.8 prove that this waiting time can be neglected, and that it does not have a perceptible effect on performance. As shown, the average dropped beacon ratio is less than 0.5 and, even under high network densities, it is still less than 2, thus not affecting DTB-MAC performance significantly.

We now analyse how these two protocols use the channel for beacon transmission, see Figure 4.9. As expected, the DTB-MAC protocol is able to use the channel more efficiently than IEEE 802.11p. IEEE 802.11p sends beacons by relying on a back-off procedure, which causes lots of collisions when increasing node density. On the contrary, DTB-MAC uses token passing, which does not cause collisions to occur between neighbouring nodes if the token circulation is done correctly. Therefore, as shown in Figure 4.9, as network density increases, DTB-MAC is able to decrease the number of collisions. This way, it increases channel usage associated to successful transmissions, thus achieving a clear improvement in terms of successful channel utilization. We notice that, although token passing is prone to cause high delays in dynamic networks, the way DTB-MAC uses the token passing mechanism does not produce more idle times compared to IEEE 802.11p, and is even able to improve the idle time for some network densities.

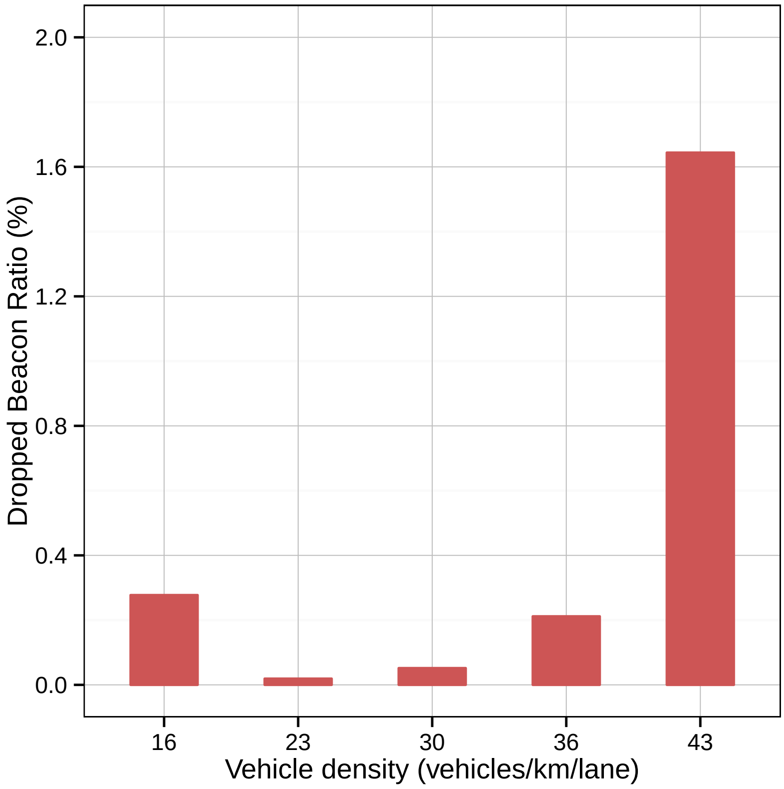


Figure 4.8: Dropped beacon ratio for the highway scenario.

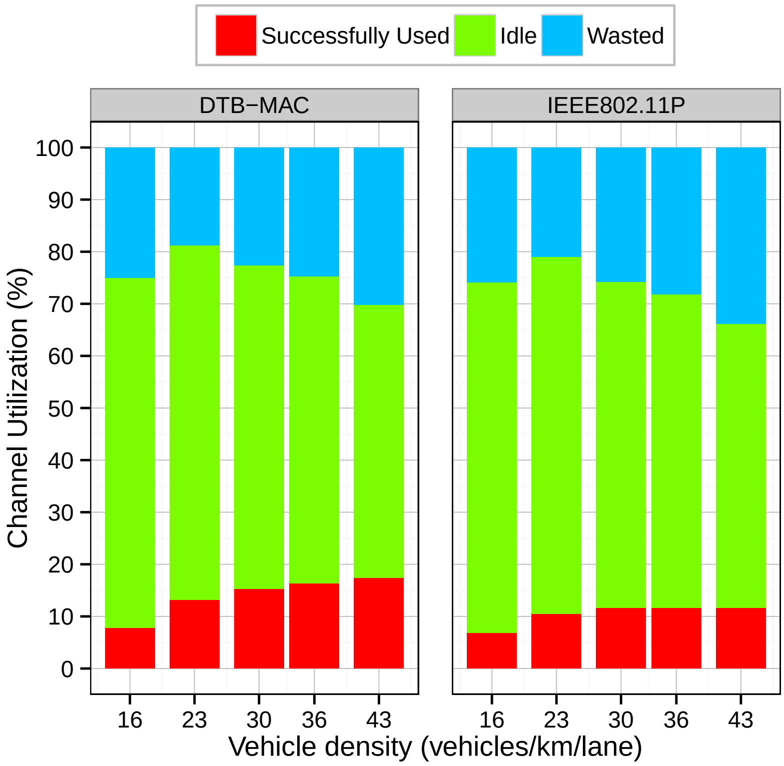


Figure 4.9: Channel utilization for the highway scenario.

4.3.2.2 Urban Scenario

Highway and urban scenarios have different characteristics. While the traffic density is one-dimensional in highways, different traffic situations take place in two-dimensional urban scenarios. However, the state of the art shows that the research community mostly focuses on highway scenarios to evaluate the performance of new solutions. Nevertheless, the statistics [BLL11] show that a substantial portion of traffic accidents occurred in urban areas. Therefore, we chose to evaluate the DTB-MAC protocol in the downtown of Milan.

Figure 4.10 explores the beacon delivery ratio for different network densities. As mentioned in the previous section, a zero delivery ratio for dropped packets was assumed for the beacon delivery ratio calculation. The results for the urban scenario are in agreement with the highway simulation results. As we expected, DTB-MAC also increases the beacon delivery ratio with nearly the same trend as in the highway scenario. This means that DTB-MAC shows more significant improvements in higher rather than lower network densities since the availability of more nodes improves token circulation. The results concerning the beacon delivery ratio under low network densities is even worse than in highway scenarios because transmissions face more obstacles. This provokes a partitioning since nodes can no longer recognize their surrounding nodes, thereby creating lots of one-member clusters, which prevents the protocol from using the token passing scheme. Moreover, since our protocol increases the waiting time, and since it is not successful at keeping the token circulating among ring members for very low densities, it shows a beacon delivery ratio that is even lower than for IEEE 802.11p.

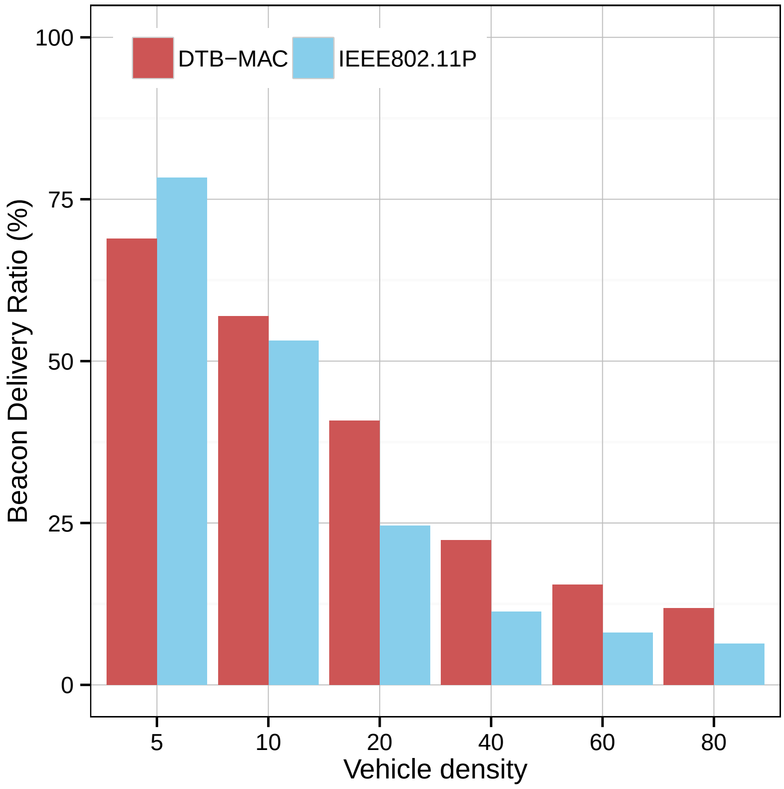


Figure 4.10: Beacon delivery ratio for the urban scenario.

In Figure 4.11, we show the average number of collisions per second for both DTB-MAC and IEEE 802.11p. This figure shows that, at low densities, DTB-MAC cannot achieve impressive improvements, as occurs at high densities. Such difference stems from the fact that, at low network densities, it is very hard for DTB-MAC to make clusters with enough members and, therefore, it relies on a random access protocol instead. However, at high network densities, and by using the clustering and token passing schemes, the number of collisions for the DTB-MAC shows significant improvements compared to the IEEE 802.11p. Although the beacon delivery ratio was lower for our method when the traffic density is equal to 5 cars per square km, the average number of collisions shows better results for our method compared to IEEE 802.11p. As we mentioned above, this occurs because our method imposes higher delays that causes a lower number of collisions (since beacons are kept for a longer time in the queue), but at low densities DTB-MAC is unable to improve the beacon delivery ratio since it is not possible to successfully circulate the token, meaning that beacons are removed due to outdatedness.

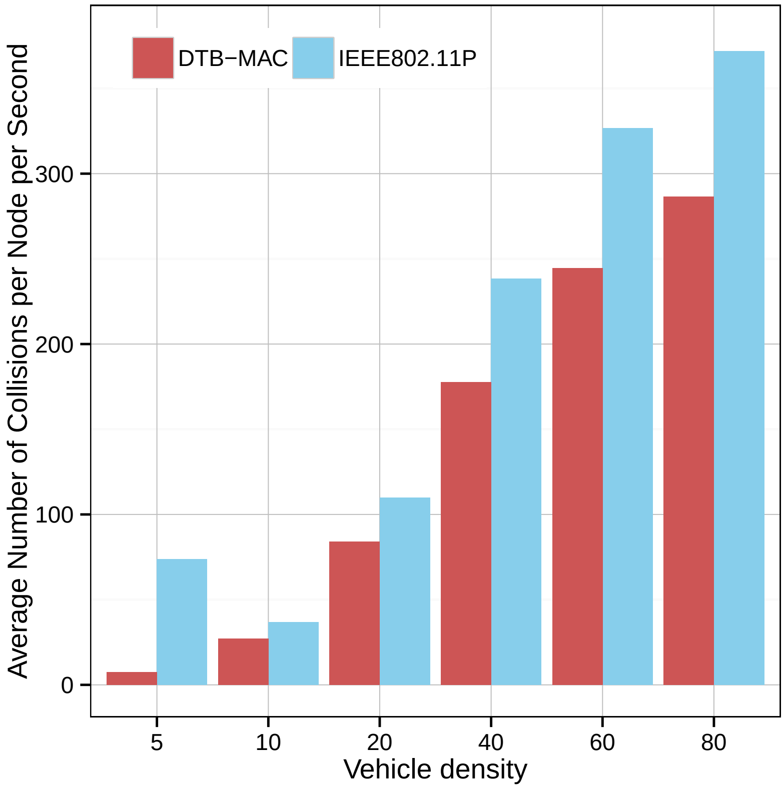


Figure 4.11: Average number of collisions per second for the urban scenario.

In Figure 4.12, we can see a descending rate from vehicle density 5 to 20, and then an ascending rate for the rest of vehicle densities. This behaviour is due to the additional challenges under low densities compared to high densities, where DTB-MAC has more chances to circulate the token with little token losses. Moreover, we need to mention that, despite the dropped beacon ratio is high at high node densities, the beacon delivery ratio shows an improvement, see Figure 4.10.

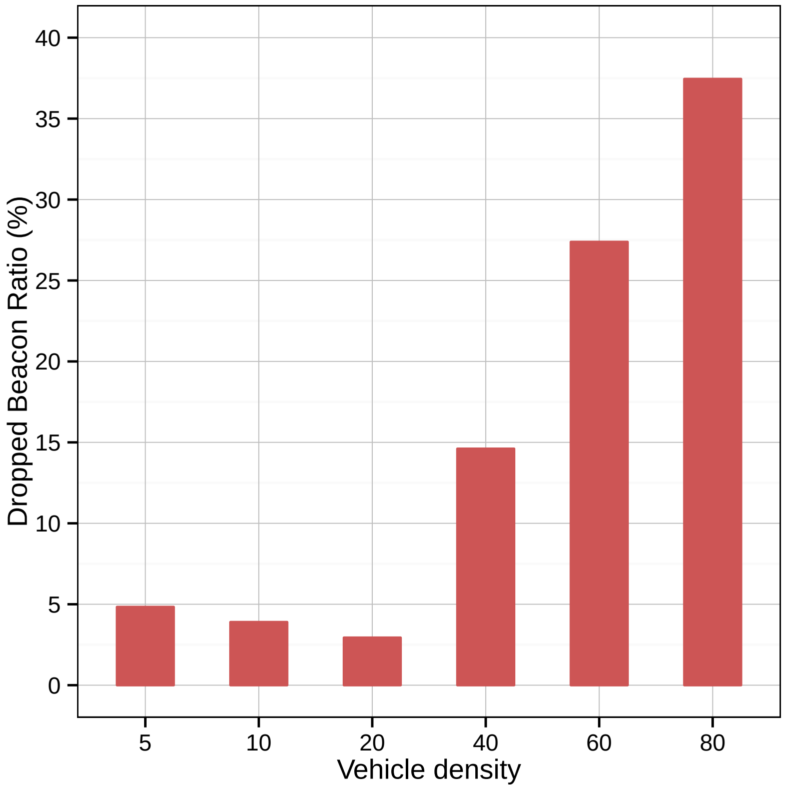


Figure 4.12: Dropped beacon ratio for the urban scenario.

DTB-MAC was also evaluated in terms of Channel utilization, as shown in Figure 4.13. As we expected, DTB-MAC clearly increases the idle time because ring members have to wait for the token, and this eliminates the probability of concurrent transmissions among the ring members. Furthermore, the channel successfully used ratio increases with increasing traffic densities, while IEEE 802.11p shows the same values for different traffic densities.

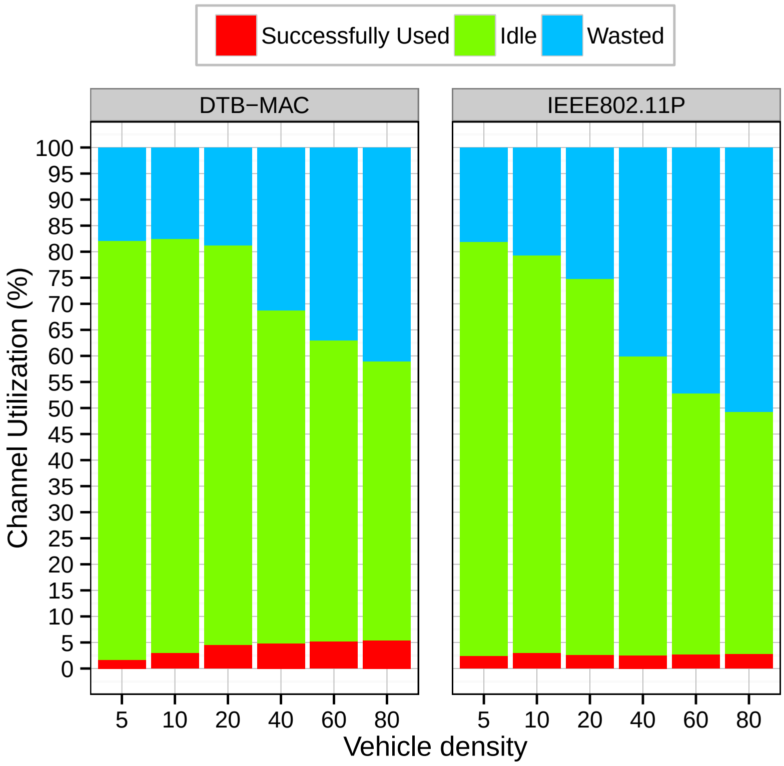


Figure 4.13: Channel utilization for the urban scenario.

Finally, we study the effect of the beacon sending rate on the DTB-MAC performance. Figure 4.14 shows that DTB-MAC performs better than IEEE 802.11p regardless of traffic density (beacon send rate, vehicle density). Moreover, the performance differences between DTB-MAC and IEEE 802.11p increase when increasing the vehicle density and/or the beacon sending rate.

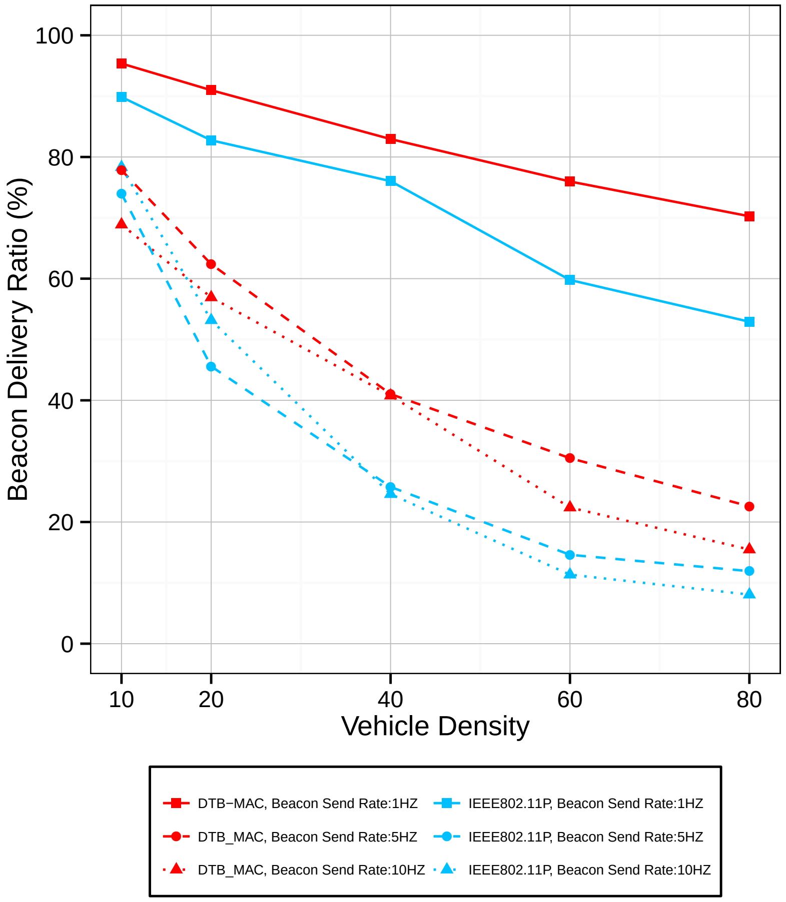


Figure 4.14: Beacon delivery ratio for different beacon sending rate in the urban scenario.

4.4 Conclusions

In this chapter we presented a new token-based MAC method to improve the performance of 802.11p for supporting driving safety applications. We started by presenting our token-based proposal, DTB-MAC, which uses a combination of a token passing mechanism and a random access MAC protocol to benefit from their advantages, being able to broadcast beacons in a reliable and efficient manner for different network densities. DTB-MAC attempts to circulate a token among ring members in order to regulate channel access, thereby reducing access times as much as possible. The obtained results show how our DTB-MAC protocol decreases the channel access collisions and improves the beacon delivery ratio. Moreover, when token passing is not possible due to node mobility and topology changes in the

VANET scenarios, DTB-MAC uses a random access MAC protocol to provide again a situation favorable to token circulation within the ring.

We compared our proposed protocol against the available standard for highway and urban scenarios, finding that DTB-MAC improves the beacon delivery ratio under different network densities; in particular, we find that the proposed solution is quite effective at high node densities, where the improvement ratio achieved is greater than 60%.

Chapter 5

Token-Based MAC Protocol for Platooning Applications

5.1 Introduction

In this chapter we focus on MAC protocols for platooning applications, specifically those requiring low-delay and reliable communications to allow the platoon to react quickly to unexpected events. As mentioned in Section 2.2, platooning applications show considerable reductions in fuel consumptions and total global carbon emissions by organizing cars into platoons, allowing vehicles to travel close to one other with short headways. Our main contribution is a token-based medium access mechanism able to transmit beacons within the required time constraints, but with a reliability level higher than IEEE 802.11p, while concurrently enabling the efficient dissemination of event-driven messages. In addition, we propose three different methods for supporting event-driven messages co-existing with beacons. We then proceed by introducing analytical and simulation results in single and multi-hop scenarios to evaluate the performance of the proposed protocol in comparison with IEEE 802.11p.

5.2 Token-Based MAC Protocol

A platoon is composed of a leading vehicle and one or more regular platoon members following the leader, each one broadcasting beacons periodically and event-driven messages whenever needed. One platoon member, the token manager, has special obligations in keeping the token passing protocol running. A one-bit flag is set on all beacons sent by the token manager in order to keep both platoon members and vehicles attempting to join the platoon informed about the token manager's identity. The token manager is preferably located in the middle of the platoon where radio coverage over the entire platoon is assumed to be best. For practical reasons, e.g. to avoid blocking highway entrances and exits for other vehicles, a platoon is limited in length. It is therefore a reasonable assumption that a platoon does not exceed a length of 500 m, which is well below the connectivity range achieved by the 802.11p physical layer. The privilege to access the channel without competition from other nodes is passed between the platoon members through the token. All messages, both periodic beacons and event-driven messages, are broadcasted, which enables piggybacking the token on a transmitted message, and notifying all platoon members about the identity of the next token holder, i.e. the vehicle that is allowed to access the channel next. Hereby, the administrative overhead of the token passing protocol is kept low.

5.2.1 Token Passing Operation

Beacons with up-to-date status information are periodically available for transmission at each individual vehicle. It is vital for the control application responsible for managing the safe platoon operation that these status updates are able to access the channel before their content becomes outdated. In order to incorporate data age into the token passing protocol, each vehicle holds a list of all other platoon members and their latest received beacon transmissions. This list is continuously updated as the vehicles listen to activities on the common channel. Whenever a platoon member receives the token, it selects the vehicle on its list with the highest data age, i.e. the oldest reception time-stamp, as the next vehicle to transmit its data. Due to the data-age-based selection of the next token holder, our proposed protocol assigns higher priorities to those vehicles that have not been successful in broadcasting their messages. We hereby use the available bandwidth to increase the reception probability of vehicles that temporarily suffer from low connectivity, and to smoothen the delay variations (jitter) throughout the platoon.

After receiving a message with the piggybacked token, the platoon member selected as the next token holder must wait for a specific period of time (depending on the role of the vehicle in the token passing process and the event-driven transmission method, as explained below) before it can begin its transmission. This waiting period, $T_{waiting}$, is a function of the propagation time, T_{prop_max}, from the first to the last vehicle in the platoon, ensuring that all vehicles have a chance to receive the last transmission before the new token holder takes action. Figure 5.1 shows an example of our token passing method where node i broadcasts its beacon and selects node j as the next transmitter. If node j receives the beacon from node i, it waits for T_{prop_max} and broadcasts its beacon. Otherwise, the token is lost and the Token Manager (TM) must re-generate a new token.

Under normal operation conditions, the maximum time between two consecutive tokens is:

$$T_{WC\_inter\_beacon} = T_{trans} + 2 \times T_{prop\_max} \tag{5.1}$$

where T_{trans} is the beacon transmission time (including a token). As long as the packet is not lost, it requires, in the worst case, an entire T_{prop_max} to reach its destination, where another T_{prop_max} is added as a waiting time before channel access is allowed.

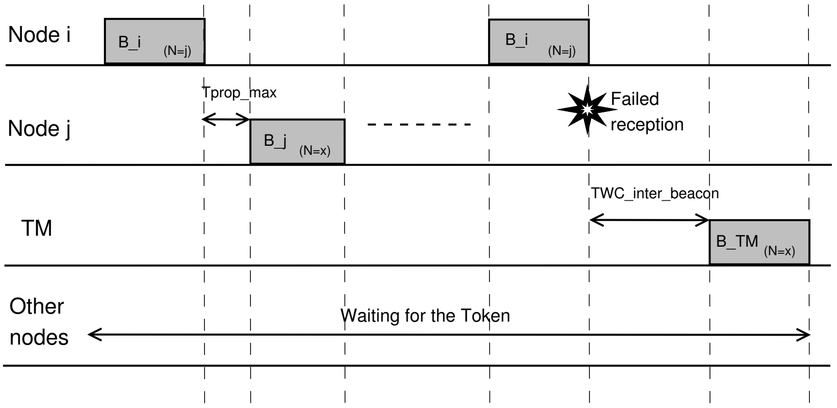


Figure 5.1: Example of the token passing operation and recovery from a lost token.

5.2.2 Ring Coordination

The token manager is responsible for handling situations that disrupt the normal operation of the token passing protocol. New vehicles joining the platoon have to be integrated into the token passing operation, while vehicles that intend to leave the platoon have to be removed from the protocol in a non-disruptive fashion. Furthermore, considering the unpredictable nature of the wireless channel in vehicular environments, nodes may get temporarily disconnected, and tokens may be lost. The token manager handles these three exceptions as follows:

- **Temporary Token Loss**

  The token manager is the one responsible for generating the first token. If a beacon is lost due to connectivity issues, the token will also be lost as it is piggybacked on the beacon itself. In case of a token loss, the token manager must re-generate the token by (re-)broadcasting its beacon and selecting a new member as the next token holder according to its current member list. Therefore, the token manager monitors the channel and, if it cannot detect any beacon transmission for $T_{WC\_inter\_beacon}$, i.e. the maximum token inter-arrival time, a new token is inserted into the platoon, and it selects the vehicle with the highest data age as its next target, as shown in Figure 5.1. In order to avoid a situation where a platoon member that is currently unreachable due to temporary connectivity problems is continuously reselected, the vehicle with the highest data age is only contacted once. If the token is not picked up, upon the next attempt to reintroduce the token it will be sent to the vehicle with the second highest data age, then to the vehicle with third highest data age, and so forth.

- **Integration of New Vehicles and Re-Integration of Temporarily Disconnected Vehicles**

  New vehicles willing to join the platoon have to be integrated into the token passing operation. Furthermore, a chance for temporarily disconnected platoon members to transmit their messages and re-join the protocol has to be provided. As mentioned above, the token manager's position in the center of the platoon ensures that it has the highest probability to receive beacons from other platoon members. However, as the platoon length increases, the probability of not being able to hear all platoon members all the time also increases. We consider the case when a transmission from one platoon member cannot be directly received by distant platoon members. In this case, whenever a member fails to receive a beacon from a distant member during one entire beacon period, it removes the member from its local list of platoon members. Note, however, that the removed member would not be removed from the local lists of all members, and thus it will eventually be chosen as the next token holder by a nearby vehicle, thereby remaining in the token loop.

A more serious problem occurs when one member is removed from the local lists of all other platoon members, including the token manager. In that rare but theoretically possible case, the removed member will be totally disconnected from the platoon. In order to allow this vehicle to rejoin the platoon, and receive the token again, we introduce a joining phase where vehicles (both new vehicles who want to join, and those who suffered from complete disconnection) get a chance to send their packets and join. The token manager will, each time it receives the token, wait for a period T_{join} until it is allowed to send its beacon. During T_{join}, vehicles compete for channel access according to the IEEE 802.11p-compliant CSMA random access protocol. Therefore, the length of T_{join} depends on the propagation time, the data packet length, and the maximum back-off time

$$T_{join} = T_{trans\_join\_request} + T_{AIFS} + T_{backoff\_max} + T_{prop\_max}. \quad (5.2)$$

where $T_{trans\_join\_request}$ is the length of the data packet carrying the request to join the platoon. A vehicle listening to the channel hears that the token manager is selected as the next token holder, and then it attempts to access the channel according to CSMA rules, i.e. it listens to the channel for an Arbitrary Inter Frame Spacing (AIFS) period and a random additional time; if the channel remains idle, it sends its packet. In case of a packet collision, it must wait to detect the next joining period as we assume that only one node can join the group in each period. T_{join} denotes the maximum time needed to accommodate one successful channel access. The token manager finishes the joining period by resuming its beacon transmission or by receiving a packet from a new member. As shown in Figure 5.2, node i broadcasts its beacon and sends the token to the token manager. The token manager delays its transmission, thereby allowing all nodes that are waiting to join the platoon to do it. If there is no joining candidate, or if a collision occurs, no one will join, and so bandwidth is wasted. In the next joining phase, node x wins the competition after waiting for a period of time equal to AIFS plus backoff, and broadcasts its beacon. The token manager resumes its transmission after T_{prop_max}.

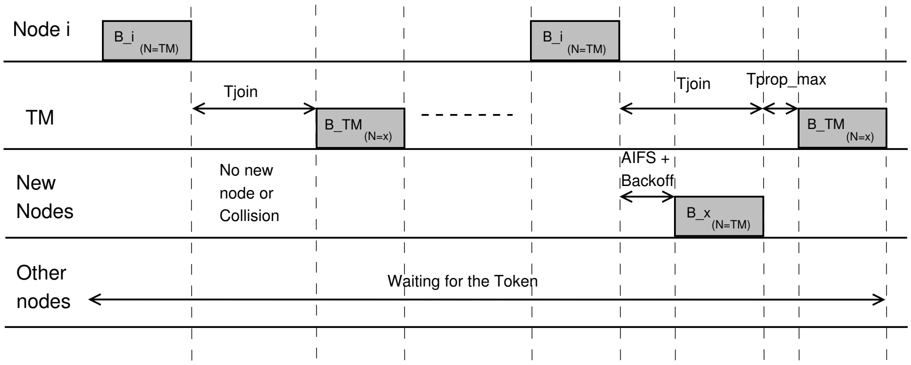


Figure 5.2: Integration of new vehicles.

- **Removing Vehicles from the Token Loop**

  Vehicles will be removed from a local member list after a time of inactivity, denoted as $T_{inactive}$.

$$T_{inactive} = N \times T_{WC\_inter\_beacon} \tag{5.3}$$

where $T_{WC\_inter\_beacon}$ is the maximum delay between two consecutive beacons according to Equation (5.1), and N is the number of vehicles in the platoon. A vehicle with short-term connectivity problems towards far-away platoon members will be temporarily removed from a few local lists, but will eventually be re-added as long as its presence remains known to some platoon members. A vehicle that intentionally leaves the platoon will eventually disappear from all local lists.

In the IEEE 802.11p standard there is no retransmission scheme for unsuccessful broadcast transmissions since there is no way to determine if reception was successful. Merely increasing the beacon update rate might just add to the problem by increasing the probability of packet collisions, lowering the performance even further [BJU13]. Our method actually proposes a built-in retransmission scheme as platoon members search in their lists and select a member based on beacon age to pass the token to. The algorithm just keeps selecting nodes with the highest data age, thereby automatically offering retransmission opportunities to those nodes that had no success for a while. This way, the transmitter side does not need any mechanisms, such as acknowledgements, to guarantee a successful reception at the receiver side. Therefore, the number of retransmissions is dynamically selected based on the current channel conditions. Our protocol also introduces a more flexible and scalable scheduling mechanism compared to TDMA-based schemes for VANETs, and specifically for platooning applications. Due to the distributed nature of the protocol, members independently manage beacon transmissions; this way, the protocol is able to automatically adapt itself to changes in the network scenario, such as the platoon size or the beacon generation frequency. On the contrary, a pre-scheduled TDMA-based retransmission scheme is much more static, requiring rescheduling and control data exchanges to adapt to changes.

5.2.3 Integration of Event-Driven Messages

We distinguish between two groups of event-driven messages. The first type is made up of highly time-critical warning messages, such as imminent collision notifications. Such information, similarly to notifications concerning sudden breaking or collision avoidance maneuvers, needs to be spread throughout the platoon with minimal delay for the sake of security. The second type is less time critical. It addresses the sporadic distribution of maintenance information, and generally originates from the platoon leader. Different event-driven message types require different services. Hence, we propose three methods to transmit event-driven messages while maintaining token-based beacon broadcasting.

1. **Event-Driven Message Transmission in Dedicated Phase**

   In this first proposed method the joining phase for the integration of new vehicles into the token loop is extended to provide room for event-driven messages. Every time the token manager holds the token, it will delay its beacon transmission to offer other platoon members an opportunity to send their event-driven messages. Similarly to the joining phase, channel access is determined through competition with other vehicles using the standard-compliant CSMA/CA MAC protocol. In order to increase the probability for an event-driven message to be received by all vehicles, it should be rebraodcasted by each vehicle upon reception. A long CSMA/CA-phase ensures that the event will spread throughout the platoon in a multi-hop fashion before the phase is over. However, the token passing process, and thereby the periodic dissemination of beacons, will be delayed. Furthermore, if there are no events to be reported, a considerable amount of valuable bandwidth will remain unexploited, meaning that valuable resources will be wasted. The frequency of the event phase depends on how often the token manager receives the token. For long platoons, this might introduce a considerable delay, especially if the event occurred right after the token manager passed on its token, and if spreading the event message throughout the platoon requires more than one event phase (worst case situation).

2. **Event-Driven Message Transmission upon Token Reception**

   In this second proposed method a vehicle sends its event-driven data whenever it receives the token. Event-driven packets and beacons are kept in separate queues and, when a vehicle holds the token, packets in the event queue get higher priority than beacons. Only when all its event-driven data are sent, the vehicle sends out its beacon, attaching it the token for the next token holder to take. Note that the token is only passed on with a beacon, not with an event-driven message. This method needs no bandwidth reservation. An event might, however, happen right after the vehicle passed on its token, meaning that it has to wait for a long time until it gets the token again, adding unwanted delay. Furthermore, considering the need for relaying event-driven data to increase the probability of successful delivery, every node that receives the event-driven message from another vehicle has to wait for the token before the message can be passed on. This adds delay between the relaying opportunities, leading to a much longer dissemination delay when compared with the first method, where the entire dissemination can be done within the duration of the reserved phase.

3. **Event-Driven Message Transmission Without Token**

   In this third and last proposed method we introduce different waiting periods for token passing and event-driven message transmissions. Vehicles with event-driven messages are allowed to be more opportunistic than the current token holder. Once a beacon (and therefore the token) transmission takes place, a countdown is started at the new token holder. The waiting time ($T_{waiting}$) is equal to one maximum propagation time (T_{prop_max}) when no event-driven traffic is considered (see Section 5.2.1). However, in this method, the waiting time for the token holder, $T_{waiting\_token}$, has to be set higher than $T_{waiting}$ to provide vehicles with event-driven data an opportunity to seize the channel before the token holder does. Therefore, when the token holder checks the channel after $T_{waiting\_token}$, it will find the channel busy because of an event-driven message transmission (if there is any event-driven message to be sent), and so it will cancel its own transmission. In contrast to the two previous methods, the token is sent along with the event-driven message. Therefore, the previously selected token holder loses its current transmission opportunity, although it has an opportunity to be selected again for data transmission by the event-driven message transmitter.

5.2.4 Multi-Hop Dissemination Method

Due to channel problems, packets from the platoon leader may not be received by a vehicle at the back of the platoon. In those cases, a dissemination strategy is needed. Specifically, intermediate vehicles who successfully received the event-driven messages should relay this information to the back of the platoon. We choose the simplest dissemination strategy for this purpose, which is flooding with one repetition. The flooding technique where vehicle is allowed to repeat each event-driven message once can provide an adequate trade-off between delay requirements for a successful platoon warning and the overall network load, avoiding to hinder other types of messages. Upon receiving an event-driven message, a vehicle keeps the message in its relaying table and re-broadcasts that message as soon as it gets channel access. We assign the highest priority to relayed messages, meaning that all available messages in the relaying table must be transmitted. Afterwards, the vehicle is allowed to send its own messages.

5.3 Performance Evaluation

To prove the correctness and completeness of our proposed solutions, in this section we rely on both analytical analysis and simulation. We first introduce the analytical analysis, and we then proceed by showing the simulation results to support our analytical results.

5.3.1 Analytical Analysis

5.3.1.1 Modeling Inter-Beacon Time (Without Event-Driven Traffic)

Equation 5.1 in section 5.2.1 showed the maximum beacon inter-arrival time, without accounting for any joining period, lost token or a phase for event-driven messages. A join period is an extra period during which joining is allowed, and it takes place after the manager gets the token (see Equation 5.2). Therefore, for N vehicles, the worst-case beacon round-trip time when no packets are lost is:

$$T_{WCbeaconRT} = N \times T_{WC\_inter\_beacon} + T_{join} \tag{5.4}$$

where T_{join} is added during the round-trip when the manager holds the token. Note that if, e.g., the last vehicle in the platoon loses a message from the token manager, the manager may get the token sooner, and thus the join period will occur more frequently. Equation 5.2 therefore represents the typical case of a fully connected platoon, where all platoon members have the same chance of getting the token.

5.3.1.2 Modelling Channel Access Delay for Event-Driven Messages

Dedicated phase for event-driven messages

We assume that join requests and event messages compete with each other in a joining phase right after the token manager gets the token. Only one message gets channel access, either the event message or the join request, and event-driven messages have a higher priority than join requests. The duration of the joining phase would be:

$$\begin{aligned} T_{join} = max(T_{trans\_event}, T_{trans\_join\_request}) + T_{AIFS} \\ + T_{backoff\_max} + T_{prop\_max} \end{aligned} \tag{5.5}$$

To calculate the worst case waiting time until an event message can access the channel, we consider the worst-case situation where an event is detected during an on-going joining phase, but too late to accommodate a packet transmission. The event packet would then have to wait for:

$$\begin{aligned} T_{WC\_event\_waiting\_time} = max(T_{trans\_event}, T_{trans\_join\_request}) \\ + N \times T_{WC\_inter\_beacon} + T_{AIFS} + T_{backoff\_max} \end{aligned} \tag{5.6}$$

i.e., the time until the current event-driven/join message is sent, plus the full token round-trip time until the manager gets the token again, plus the worst case time to get CSMA channel access in the next joining phase.

Event-driven message transmission after token reception

In this context, the worst-case beacon round-trip time must be extended to the situation where every vehicle has an event message to send every time it gets the token:

$$T_{WC\_inter\_beacon\_event} = T_{trans\_event} + T_{trans\_beacon} + 2 \times T_{prop\_max} \tag{5.7}$$

$$T_{WCbeaconRT\_event} = N \times T_{WC\_inter\_beacon\_event} + T_{join} \tag{5.8}$$

If we assume that, for each message in the relaying table, a single transmission is required to reach all platoon members, we have to add the worst-case waiting time where all vehicles already have N-1 messages in their relaying table. Therefore, they have to send all packets in their tables before sending their own packets, and this adds more delay to the $T_{WC\_inter\_beacon\_event}$ as follows:

$$\begin{aligned} T_{WC\_inter\_beacon\_event\_relay} = {} & T_{trans\_event} + T_{trans\_beacon} \\ & +(N-1) \times T_{trans\_event} + 2 \times T_{prop\_max} \end{aligned} \tag{5.9}$$

Event-driven message transmission without token

In this situation we extend the $T_{waiting\_token}$ to $2 \times T_{prop\_max}$ in order to offer any vehicle with a pending event the chance to seize the channel after a waiting time of $T_{waiting\_event}$ lasting for one T_{prop_max} plus a random backoff time. This changes all the worst-case calculations for beacon transmissions under section 5.2.1.

The event, in the worst case, is detected just when another vehicle obtains the token, and therefore our vehicle has to wait until the next time the token is passed to opportunistically seize the channel. In the worst case, the vehicle that just got the token is the token manager, and so we have to add the joining phase:

$$\begin{aligned} T_{WC\_event\_waiting\_time} = {} & T_{trans\_beacon} + T_{prop\_max} + T_{waiting\_event} \\ & +T_{join} + T_{backoff\_max} \end{aligned} \tag{5.10}$$

5.3.2 Simulation Settings

To assess the effectiveness of the proposed protocol we rely on computer simulations, where we use the analytical evaluation from Section 5.3.1 to verify the simulator. In this section, we describe the simulation details, including simulation scenario parameters and protocol configurations.

We simulate platoons of five vehicles on a highway, a setting commonly used for platooning applications [BJC14], with an antenna-to-antenna spacing of 30 m. We used SUMO in order to generate realistic vehicular mobility models. Also, we implemented our proposed MAC protocols in OMNeT++ (version 4.4.1), and used the IEEE 802.11p implementation made available by the Veins framework (version 2.1) for OMNeT++ for performance comparison purposes. Tables 5.1 and 5.2 summarize the simulation and protocol parameters.

Table 5.1: Simulation parameters.

Simulation Parameters	**Value**
Simulation time	20 s
Platoon size	5 and 10 vehicles
Propagation model	Simple path loss + Long-normal shadowing
Antenna-antenna spacing	30 m
Frequency	5.9 GHz
Beacon frequency	50 and 100 Hz
Beacon length	400 bytes
Event-driven message frequency	20 Hz
Event-driven message length	400 bytes
Data Rate	6 Mbps
Transmission range	500 m
Time slot	13 μs
SIFS time	32 μs

Table 5.2: Protocol parameters.

Parameter	**Value**
$T_{waiting}$ (T_{prop_max})	0.5 ms
$T_{waiting\_event}$	0.5 ms
$T_{waiting\_token}$	1 ms

In accordance with the ETSI standard, we use 400 byte packet sizes for beacon and event-driven messages. Beacons and event-driven messages are generated every 20 ms and 50 ms, respectively. Also, packets are broadcasted with a data rate of 6 Mbps within a transmission range of 500 m. Similarly to [AEO15], we combine simple path loss and log-normal shadowing models, which are common models for highway simulation. Also, the parameters of these models were chosen according to that same paper. We ran each simulation for 20 seconds. The beacon and event-driven priorities are AC[0] and AC[1], respectively.

The metrics used to evaluate the performance of the MAC protocols are summarized as follows: (a) Packet Delivery Ratio (PDR) of event-driven messages, which represents the ratio between the total number of packets received by the final destinations and the packets originated by the source; (b) average channel access delay of event-driven messages, which represents the average time a packet must wait before access to the channel is granted; and (c) Inter-Reception Time (IRT) of periodic beacons, which is calculated as the time interval between the sequential reception of beacons from each member averaged over all platoon members. The IRT parameter reflects the data age of the beacon content as it monitors the age of the information a node holds from a specific neighbor once a new beacon arrives. Maintaining an IRT close to the beacon period is vital to the successful implementation of a platoon control application.

5.3.3 Simulation Results and Analysis

In order to show the advantages of the proposed protocol, we evaluate it under both single and multi-hop broadcasting scenarios. Since this thesis is mainly focused on single-hop broadcasting, we first show a detailed analysis for single-hop broadcasting; then, we evaluate the best performing single-hop solutions and their ability to support multi-hop broadcasting. IEEE 802.11p is used as reference, and we compare the delay and the reliability of our protocol for supporting beacons and event-driven messages.

5.3.4 Single-Hop Broadcasting

In order to quantitatively evaluate the proposed mechanism, we first compare our main protocol without considering event-based traffic against IEEE 802.11p for different numbers of vehicles and beacon frequencies. For this purpose, we determine the beacon inter-reception time to show the efficiency of the system in reception of safety messages within time constraints, as well as the reliability of beacon delivery.

For a beacon frequency of 50 Hz and a platoon with 5 vehicles, Figure 5.3 shows that our protocol clearly outperforms IEEE 802.11p. The figure also shows that our protocol keeps an IRT below 20 ms, which means it can deliver all beacons before the next beacon generation. In this case, the built-in retransmission scheme of our protocol has a fundamental role to achieve these results since each beacon gets a chance to be broadcasted depending on the current channel situation. As all intra-platoon communication takes place on a dedicated service channel, we can fully utilize the available bandwidth without interfering with the performance of other VANET applications. Also, it allows us to support a higher-frequency beacon generation for safety applications that require it. For IEEE 802.11p, since all vehicles try to access the channel in a short time window after each beacon generation time, and since there is no retransmission opportunity, there is a high probability of collision, which causes beacon inter-reception times of more than 20 ms. Moreover, as shown in figure 5.3, the longest inter-reception time for IEEE 802.11p amounts to 120 ms, rendering vehicles invisible to their neighbors for

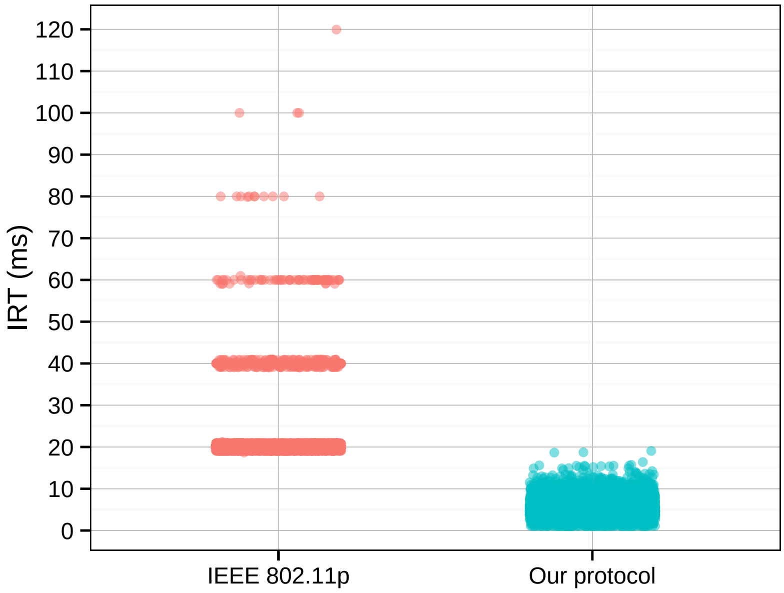


Figure 5.3: IRT for a platoon with 5 vehicles and beacon frequency of 50 Hz.

large time periods due to repeated beacon collisions, thereby endangering the safe operation of the platoon.

In Figure 5.4, we evaluate the performance of our protocol for two different platoon sizes of 5 and 10 vehicles, when the beacon frequency is equal to 50 Hz. Complementing Figure 5.3, this figure shows that, when the platoon size is increased to 10 vehicles, our protocol cannot maintain the IRT below one beacon generation interval. However, it can still keep the maximum IRT below three beacon generation intervals, and deliver 97% of the beacons before 20 ms, while the maximum IRT obtained for IEEE 802.11p is equal to 300 ms.

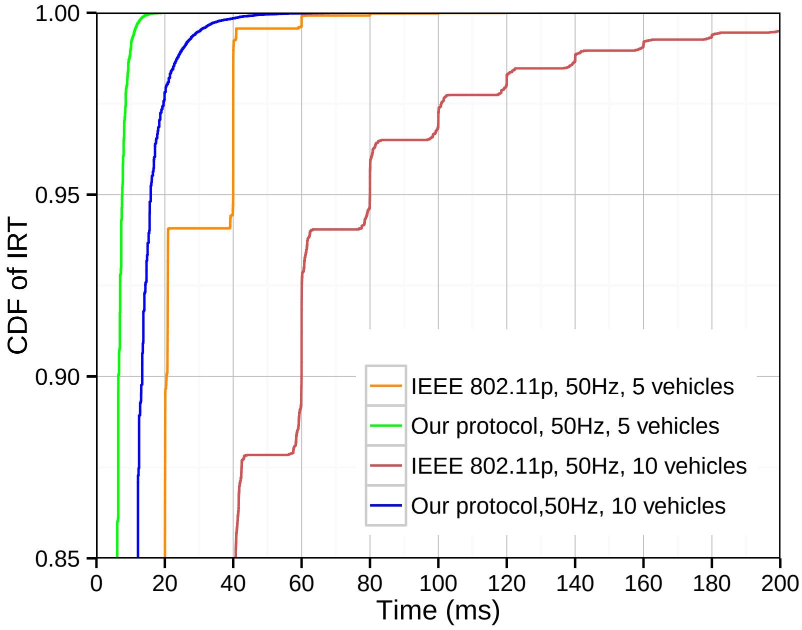


Figure 5.4: IRT for beacon frequency of 50 Hz.

A beacon frequency of 50 Hz is often mentioned by truck manufacturers as the target frequency for platooning applications. In order to evaluate the performance of our protocol under more challenging conditions, we increased the beacon frequency to 100 Hz. As shown in Figure 5.5, this causes IRT also experience an increase. So, for IEEE 802.11p, if previously 92% of inter-reception times are less than three beacon generation intervals for a beacon frequency of 50 Hz, this number goes down to 85% for a frequency of 100Hz. Notice that, since our protocol keeps the token circulating, a received token is used as a retransmission opportunity at low beacon frequencies whenever there is no new beacon. With increasing beacon frequency, however, the beacon generation interval decreases, and so the number of retransmission opportunities is also decreased. Therefore, the available bandwidth is instead used for broadcasting new beacons, although performance improvements are still obtained with fewer retransmissions.

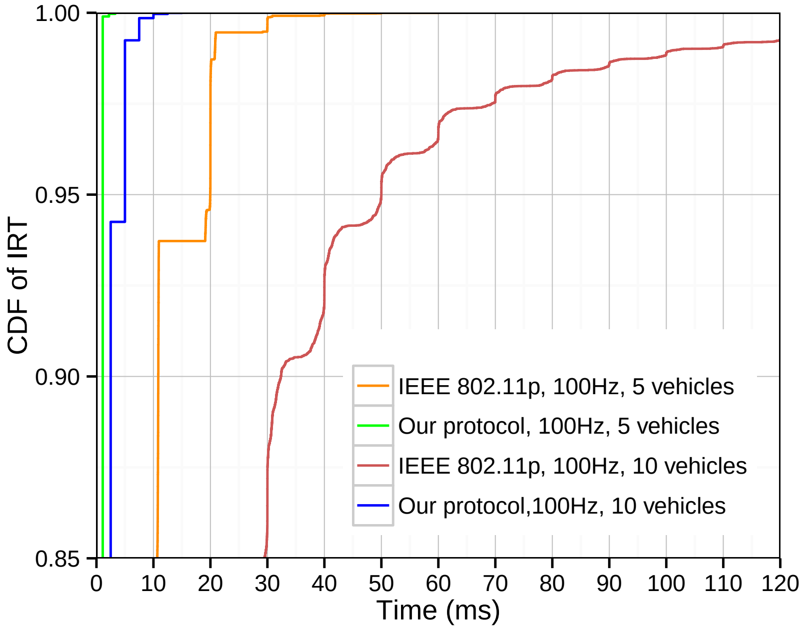


Figure 5.5: IRT for beacon frequency of 100 Hz.

As mentioned above, we proposed three different methods for supporting event-driven messages. Figure 5.6 shows the IRT of beacons in our token-based MAC protocol with and without the presence of event-driven traffic in the network, along with performance results for IEEE 802.11p. Notice that, for the following figures, we only focus on beacon transmissions at a frequency of 50 Hz. In the case of IEEE 802.11p, beacons and event-driven traffic attempt to access the channel only once per assigned period. The IRT of IEEE 802.11p beacons shown in Figure 5.6 lies, therefore, mostly near the 20 ms mark, which is the beacon period defined. Delayed channel access due to contention leads to beacon IRTs that are longer or shorter than exactly one period, as shown in the graph for IEEE 802.11p. The proposed token passing scheme, on the other hand, retransmits beacons within one period as long as there are resources available. Therefore, considerably shorter IRT values are achieved. As expected, the case where no event-driven traffic is present in the network is associated to the lowest IRT values. The introduction of event-based traffic, regardless of the method chosen, utilizes bandwidth for event-based packets instead of beacon retransmissions, and therefore shows a slight increase of IRTs. If event-driven messages are sent during a dedicated phase or upon token reception, they simply occupy the bandwidth that would otherwise be used for beacon retransmissions, and thus they have only a small influence on the IRT. On the contrary, the third method, where event-based messages can be sent without waiting for the token, actually interferes with the token passing order, resulting in decreased beacon performance. According to Equation (5.4), the maximum round-trip time without considering token losses is equal to 9.4 ms. As shown

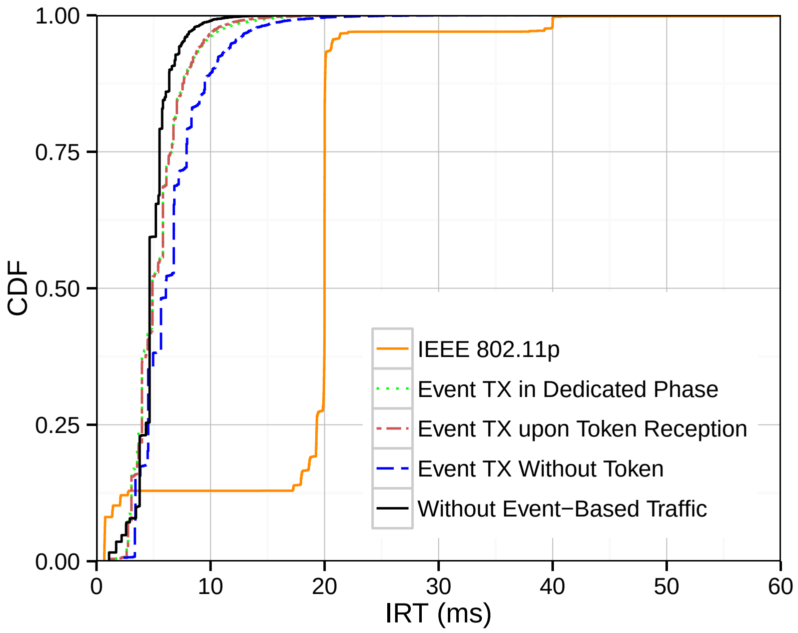


Figure 5.6: CDF of IRT for single-hop broadcasting.

in the figure, the maximum IRTs is in general about 10 ms, being higher values related to token losses.

The channel access delay of event-driven messages for IEEE 802.11p and our proposed methods is shown in Figure 5.7. As expected, IEEE 802.11p obtains shorter delays for event-driven messages since it uses a random access method and, therefore, event-driven messages are sent as soon as the channel is found to be idle. The opportunistic approach for the transmission of event-based packets without token possession shows the best performance, as it allows time-critical event-based traffic to access the channel as soon as the need arises. The delay increases if an event-driven message generated by a certain vehicle has to wait until that specific vehicle happens to get the token before it can be sent, as occurs in the “Event TX upon Token Reception” method. The delay is even longer when a vehicle has to wait for the event phase in order to send its event packet (“Event TX in Dedicated Phase”). That phase is then shared by all event-driven messages generated by different platoon members since the last event phase took place, leading to contention and further delays. The “Event TX Without Token” method achieves channel access delay results close to those of IEEE 802.11p since the event-driven messages benefit from a higher priority than beacons, and also because the normal beacon transmission routine is interrupted to provide room for event-driven message transmission. Based on Equations (5.6), (5.8) and (5.10), the channel access time for event-driven messages for the “Event TX in Dedicated Phase”, “Event TX upon Token Reception”, and “Event TX Without Token” methods are 9, 11.8, and

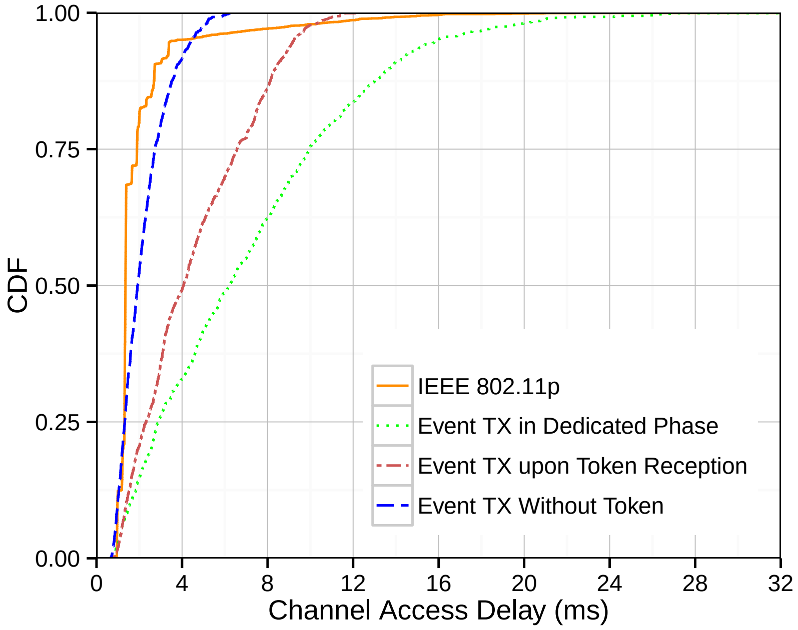


Figure 5.7: CDF of channel access delay for single-hop broadcasting.

3.1 ms, respectively. Figure 5.7 shows that the simulation results are only compliant with the numerical results for the "Event TX upon Token Reception" method since, in this method, the event-driven transmission routine does not interfere with the token passing routine. Concerning the other methods proposed, the number of collisions increases since event-driven message transmissions interfere with the beacon transmission routine, which is not considered by the numerical analysis.

Although IEEE 802.11p obtains a lower channel access delay, notice that the delivery ratio for event-driven messages achieved by our protocol is higher than for 802.11p, as shown in Table 5.3. The results show that waiting for the token allows achieving the best delivery ratio since it does not interfere with the normal beacon transmission routine for event-driven messages, which leads to fewer collisions. Also, introducing a dedicated phase for event-driven traffic once per token period represents the worse case among our proposed methods since, for this solution, all platoon members must compete with each other in every period in order to send their event-driven messages, and they must compete with join requests from non-platoon members as well. Moreover, table 5.3 shows that the delivery ratio distribution for all platoon members is nearly uniform since collisions decrease as nodes become synchronized with the token passing procedure by taking the propagation delay into account.

Overall, simulation results show that the "Event TX upon Token Reception" method is best when transmission reliability is the most important factor, while the "Event TX Without Token" method is preferable for time-critical warning

Table 5.3: Average event-driven message delivery ratio for single-hop broadcasting.

Average Event-Driven Message Delivery Ratio (%)				
Vehicle ID	IEEE 802.11p	Event TX in Dedicated Phase	Event TX upon Token Reception	Event TX Without Token
1	77.00	87.00	95.25	88.25
2	84.00	87.00	96.25	87.25
3	85.00	87.00	97.00	87.00
4	83.00	87.00	96.50	88.25
5	77.00	87.00	96.00	89.87
Average	**81.20**	**87.00**	**96.20**	**88.14**

messages due to its lower channel access delay. Furthermore, keeping the beacon data age-based token selection intact reduces the negative impact of event-driven traffic on the beacon performance. This should be considered in favor of the “Event TX upon Token Reception” method.

5.3.5 Multi-Hop Broadcasting

As we mentioned above, the main focus of our proposed protocol is single-hop broadcasting. Nevertheless, in order to increase the probability that all platoon members successfully receive event-driven messages, we extend our protocol to enable multi-hop message delivery. By introducing multi-hop relaying features, each event-driven message is rebroadcasted once upon reception. This way, the chances of reaching all platoon members with information about a specific event increase. With the exception of the “Event TX in Dedicated Phase” method, which shows the worse performance in terms of event-driven message delivery and channel access delay for single-hop broadcasting, we have extended all methods with multi-hop features for further comparison.

Figure 5.8 shows the IRTs for IEEE 802.11p and our protocol. As shown, the performance levels achieved by the “Event TX upon Token Reception” method are quite close to those achieved without event-driven traffic. Notice that, since event-driven message transmission in the “Event TX upon Token Reception” method does not interfere with the normal beacon routine, IRTs for single and multi-hop broadcasting show a very similar trend. In contrast, the performance of the “Event TX Without Token” method is degraded since this method interferes with the token passing to broadcast or forward event-driven messages, thereby causing several collisions and increasing IRT values. Compared to the single hop case, IEEE 802.11p performance decreases when introducing multi-hop broadcasting due to the increased traffic volume.

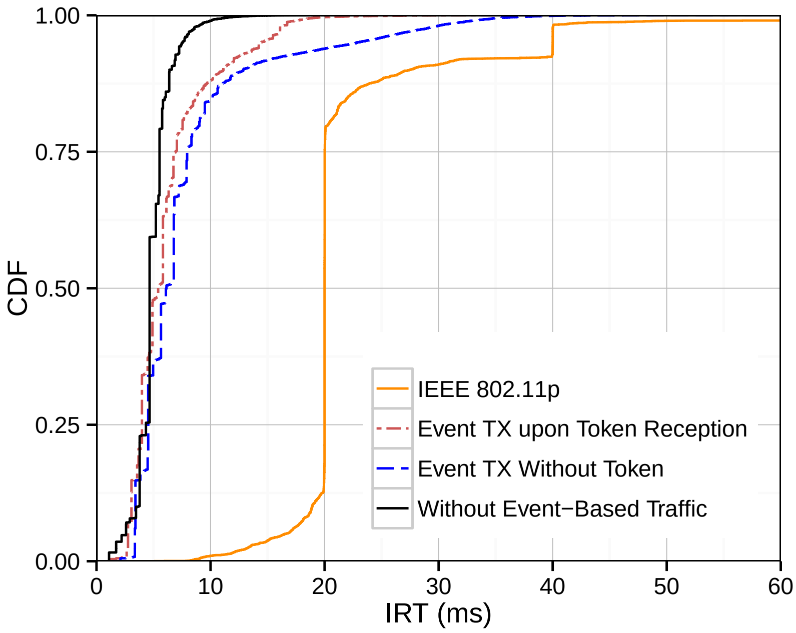


Figure 5.8: CDF of IRT for multi-hop broadcasting.

Figure 5.9 shows the channel access delay for IEEE 802.11p and our protocols. As expected, IEEE 802.11p achieves better performance compared to our methods in terms of delay since 802.11p allows immediate access to the channel as soon as it is idle. Instead, for the “Event TX upon Token Reception” method, a vehicle carrying an event-driven message to send must wait for the token before transmitting or relaying. However, the maximum delay achieved by our protocol never exceeds 20 ms, thereby meeting the required delay bound for safety applications [SAE10]. In contrast to single-hop broadcasting, the “Event TX Without Token” method shows a longer channel access delay than the “Event TX upon Token Reception” method due to the high traffic load associated to message relaying. In the “Event TX Without Token” method, after any event-driven message reception, all platoon members attempt to forward such message using CSMA/CA, much like with IEEE 802.11p. Therefore, the probability of collision is increased, which also leads to increased channel access times.

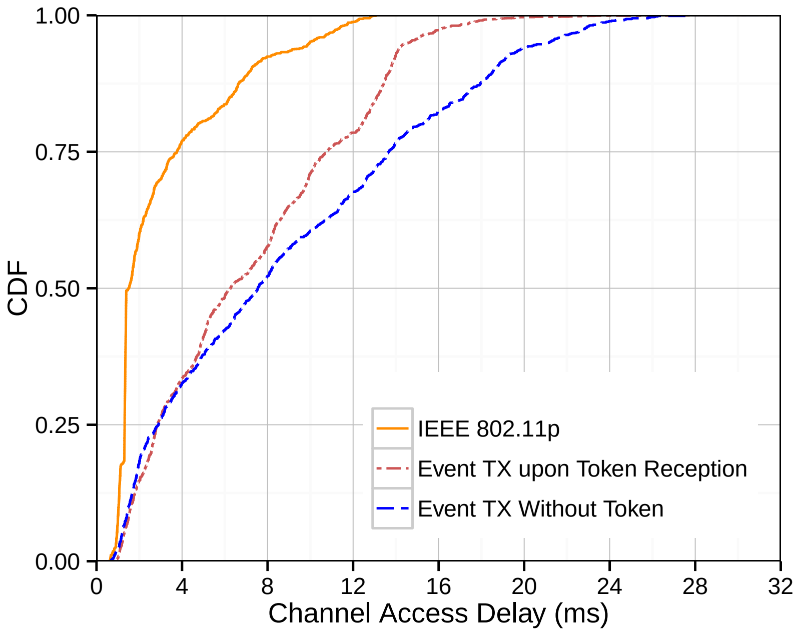


Figure 5.9: CDF of channel access delay for multi-hop broadcasting.

Complementing Figure 5.9, Table 5.4 shows that, although our protocol obtains higher channel access delays than 802.11p, it has better delivery ratios, meaning that the "Event TX upon Token Reception" method successfully delivers all event-driven messages by rebroadcasting each event-driven message received once. Therefore, our protocol is able to meet safety applications' requirements by successfully delivering event-driven packets within the deadline while, at the same time, it is able to maintain a beacon delivery effectiveness of at least one beacon every beacon interval.

Table 5.4: Average event-driven message delivery ratio for multi-hop broadcasting.

Average Event-Driven Message Delivery Ratio (%)			
Vehicle ID	IEEE 802.11p	Event TX upon Token Reception	Event TX Without Token
1	92.75	100	94.00
2	87.25	100	91.50
3	89.50	100	90.75
4	90.00	100	91.00
5	87.25	100	94.00
Average	**89.35**	**100**	**92.35**

5.4 Conclusions

In this chapter, we presented a token-based MAC protocol for platooning scenarios providing timely and reliable inter-vehicle communication for beacon and event-driven messages. The proposed protocol has the following features: (a) The protocol uses a token to achieve non-competitive channel access; (b) It automatically provides retransmission opportunities for platoon members based on data age; (c) It is able to integrate new vehicles into the platoon and remove those vehicles that intend to leave the platoon in a non-disruptive fashion. In addition, three different extensions to the protocol were proposed to support low-delay delivery of event-driven messages, while having a small impact on the transmission frequency of beacon messages.

Analytical and simulation-based evaluations have been provided for single and multi-hop broadcasting scenarios. The results show that, on the one hand, the proposed method is able to fulfil the requirements of beacon transmission, guaranteeing beacon delivery within one beacon generation interval. On the other hand, it shows that different methods for disseminating event-driven messages are useful for different types of events, thereby being able to meet the requirements of a wide variety of safety applications. We find that our protocol against the available standard and it clearly outperforms the standard for beacon transmission in single and multi-hop scenarios. Furthermore, it shows a better delivery ratio and limited delay degradation for event-driven messages. As additional advantages, our token-based method is decentralized, not requiring synchronization nor any extra overhead for control traffic, thereby providing seamless adaptation to changes in the beacon frequency and the number of platoon members.

Chapter 6

Conclusions, Publications and Future Work

6.1 Conclusions

In this thesis we studied existing MAC solutions to enhance the performance of the IEEE 802.11 family of standards, including the 802.11p amendment for vehicular environments. Moreover, we developed completely new medium access mechanisms to improve the overall performance of vehicular networks in both highway and urban scenarios. In order to accurately evaluate previously proposed protocols, as well as our own proposals, we provided a simulation framework to simulate realistic vehicular scenarios. We now proceed to summarize the most relevant contributions of this thesis:

- A survey of the most significant proposals found in the literature concerning MAC protocols, including enhancements to IEEE 802.11 and 802.11p for optimally adjusting the CW sizes in MANET and VANET environments, existing solutions to improve the delay and the reliability of IEEE 802.11p in both highway and urban scenarios, as well as proposals supporting platooning applications with timely and reliable MAC protocols.

- A simulation framework able to simulate and evaluate previously proposed protocols, as well as our new contributions. We studied different available network and traffic simulation tools, and we also explored different propagation models in order to select the most suitable one for accurately simulating vehicular environments. In addition, the simulation scenarios used throughout this thesis relied on real maps extracted from online open source maps, and include real obstacles.

- Proposal of novel MAC protocols, HBCWC and DDCWC, in order to optimally adjust the backoff ranges with low-overhead for different nodes of a MANET, thereby improving the packet delivery ratio and the average end-to-end delay for unicast applications.

- An enhanced version of the IEEE 802.11p MAC protocol, DBM-ACW, that provides a better support for unicast applications in vehicular environments (including both highway and urban scenarios) in terms of delay and reliability.
- DTB-MAC, a new token-based MAC method to improve the performance of 802.11p when supporting driving safety applications. We used a combination of a token passing mechanism and a random access MAC protocol to be able to broadcast beacons in a reliable and efficient manner for different network densities. DTB-MAC attempts to circulate a token among ring members in order to regulate channel access, thereby decreasing the channel access collisions and improving the beacon delivery ratio.
- A new proposal for platooning scenarios to provide timely and reliable inter-vehicle communication for beacon and event-driven messages. The proposed protocol is decentralized, not requiring synchronization nor extra overhead for control traffic. This way, it provides seamless adaptation to changes in the beacon frequency and the number of platoon members. Moreover, it uses a token to achieve non-competitive channel access, automatically offering retransmission opportunities to platoon members based on data age. In addition, it provides three different techniques to support low-delay delivery of event-driven messages, while having a small impact on the transmission frequency of beacon messages.

6.2 Publications Related to the Thesis

The research work related to this thesis has resulted in 13 publications; among them we have 1 book chapter, 6 journal articles (2 of them indexed by the Journal Citation Reports (JCR) database) and 6 conference papers (2 of them indexed by the Computer Science Conference Ranking or the Computing Research and Education (CORE) lists). A list of all publications and a brief description of them is shown below.

6.2.1 Book Chapters

[BCCM15b] Ali Balador, Carlos T. Calafate, Juan-Carlos Cano and Pietro Manzoni. "New challenges in a vehicular ad-hoc network environments: A MAC Layer Perspective.", in *Simulation Technologies in Networking and Communications: Selecting the Best Tool for the Test, CRC Press*, 2015.

This book chapter provides an overview of 802.11/802.11p, as well as alternatives presented by the research community to address the detected limitations in vehicular scenarios. In addition, we studied why using simulation methodology is a relevant issue, and how to properly configure simulation settings for vehicular environments. Analysis and simulation results using OMNeT++ in vehicular scenarios, including highway and urban scenarios, show that alternatives to 802.11p able to perform contention window adjustments are able to improve the overall performance, even for high network density scenarios.

6.2.2 Journal Publications

[BCJ⁺16] Ali Balador, Annette Bohm, Elisabeth Uhlemann, Carlos T. Calafate, Yusheng Ji and Juan-Carlos Cano. "A Reliable Token-Based MAC Protocol Supporting Beacons and Event-Driven Messages in Platooning Applications.", in *Journal of IEEE Transactions on Vehicular Technology*, Under Review.

In this article we proposed a token-based medium access mechanism able to transmit beacons within required time constraints, but with a higher reliability level than IEEE 802.11p, while concurrently enabling efficient dissemination of event-driven messages. The protocol circulates the token within the platoon based on beacon data age, thereby automatically offering repeated beacon transmission opportunities for increased reliability. In addition, we proposed three different methods for supporting event-driven messages coexisting with beacons. Analysis and simulation results in single and multi-hop scenarios are presented to evaluate the performance of the proposed protocol and compare it to IEEE 802.11p. It is shown that, by providing non-competitive channel access and frequent retransmission opportunities, our protocol can guarantee beacon delivery within one beacon generation interval, while fulfilling the requirements on low-delay dissemination of event-driven messages for traffic safety applications.

[BCCM16] Ali Balador, Carlos T. Calafate, Juan-Carlos Cano and Pietro Manzoni. "A Density-Based Contention Window Control Scheme for Unicast Communications in Vehicular Ad Hoc Networks.", in *International Journal of Ad Hoc and Ubiquitous Computing, In Press.* (JCR 2014: 0.56)

In this article we proposed DBM-ACW, a novel contention window control scheme for VANET environments based on estimating the network density, which is then used to dynamically adapt the CW size. Analysis and simulation results using OMNeT++ in vehicular scenarios, including highway and urban scenarios, show that DBM-ACW provides better overall performance compared with previous proposals, even in high network density scenarios.

[BGMJ10] Ali Balador, Mahtab Ghasemivand, Ali Movaghar and Sam Jabbehdari. "An Adaptive Contention Window Control for Improving DCF Throughput and Fairness.", in *European Journal of Scientific Research (EJSR)*, Volume 136, Number 1, 2016.

[BMJ10b] Ali Balador, Ali Movaghar and Sam Jabbehdari. "History Based Contention Window Control (HBCWC) in IEEE 802.11 Mac Protocol in

Error Prone Channel.", in *Journal of Computer Science (JCS)*, Volume 6, Number 2, Pages 205-209, 2013.

[BMJ10a] Ali Balador, Ali Movaghar and Sam Jabbehdari. "Efficient Contention Window Control with Two-Element Array.", in *Journal of Computing (JoC)*, Volume 2, Number 8, Pages 13-18, 2013.

[BMJK12] Ali Balador, Ali Movaghar, Sam Jabbehdari and Dimitris N. Kanellopoulos. "A novel contention window control scheme for IEEE 802.11 WLANs.", in *Journal of IETE Technical Review*, Volume 29, Number 3, Pages 202-212, 2012. (JCR 2014: 0.89)

In these four articles we proposed dynamic contention window control schemes, in which the backoff ranges are adjusted based on network history, which is kept in a Channel State (CS) vector. After successful transmissions and collisions, network nodes change their CW based on the status of their CS vectors. Extensive simulation studies show that our enhancements outperform available standards and most significant existing solutions in terms of packet delivery ratio and average end-to-end delay.

6.2.3 International Conferences

[BBU^{+}15a] Ali Balador, Annette Bohm, Elisabeth Uhlemann, Carlos T. Calafate and Juan-Carlos Cano. "A Reliable Token-Based MAC Protocol for Delay Sensitive Platooning Applications.", in *Proc. IEEE VTC2015-FALL*, Boston, USA, 6-9 September, 2015. (CORE B)

In these two papers, we proposed a token-passing medium access method where the next token holder is selected based on beacon data age. This has the advantage of allowing beacons to be re-broadcasted in each beacon interval whenever time and bandwidth are available. We showed that our token-based method is able to reduce the data age and considerably increase reliability compared to pure 802.11p.

[BCCM15a] Ali Balador, Carlos T. Calafate, Juan-Carlos Cano and Pietro Manzoni. "DTB-MAC: Dynamic Token-Based MAC Protocol for Reliable and Efficient Beacon Broadcasting in VANETs.", in *Proc. IEEE CCNC 2015*, Las Vegas, Nevada, USA, 9-12 January, 2015. (CORE B)

In this paper, we proposed a hybrid MAC protocol, referred as Dynamic Token-Based MAC Protocol (DTB-MAC). DTB-MAC uses both a token passing mechanism and a random access MAC protocol to prevent channel contention as much as possible, and to improve the reliability of safety message transmissions. Our proposed protocol tries to select the best neighbouring node as the next transmitter, and when it is not possible, or when it causes a high overhead, the random access MAC protocol is used instead. Based on simulation experiments, we showed that the DTB-MAC protocol can achieve better performance than IEEE 802.11p in terms of channel utilization and beacon delivery ratio.

[BCJ$^+$13b] Ali Balador, Carlos T. Calafate, Juan-Carlos Cano and Pietro Manzoni. "Congestion Control for Vehicular Environments by Adjusting Contention Window size in IEEE 802.11.", in *The 13th International Conference on Algorithms and Architectures for Parallel Processing (ICA3PP-2013)*, Vietri sul Mare, Italy, 18-20 December, 2013.

[BCCM13] Ali Balador, Carlos T. Calafate, Juan-Carlos Cano and Pietro Manzoni. "Reducing Channel Contention in Vehicular Environments Through an Adaptive Contention Window Solution.", in *6th Wireless Days Conference (WD2013)*, Valencia, Spain, 13-15 November, 2013.

In these three papers, we proposed new contention window control schemes for VANET environments based on estimating the network condition. Analysis and simulation results using OMNeT++ in urban scenarios show that our proposed protocols clearly outperform 802.11, even under very high network density, by increasing the packet delivery rate while decreasing the number of collisions and the end-to-end delay for unicast applications.

6.2.4 Other Publications

[BBU$^+$15b] Ali Balador, Annette Bohm, Elisabeth Uhlemann, Carlos T. Calafate, Yusheng Ji, Juan-Carlos Cano and Pietro Manzoni. "An Efficient MAC Protocol for vehicle platooning in automated highway systems.", in *XXVI Jornadas Sarteco*, Cordoba, Spain, 23-25 September, 2015.

[BCJ$^+$13a] Ali Balador, Carlos T. Calafate, Juan-Carlos Cano and Pietro Manzoni. "A Novel 802.11 Contention Window Control Scheme for Vehicular Environments.", in *XXIV Jornadas Sarteco*, Madrid, Spain, 17-20 September, 2013.

[SJBK13] Anahita Sanandaji, Ali Balador, Sam Jabbehdari and Dimitris N. Kanellopoulos. "MAC layer misbehavior in MANETs.", in *Journal of IETE Technical Review*, Volume 30, Number 2, pages 324-335, 2013. (JCR 2014: 0.89)

6.3 Future work

In the development of this thesis several issues emerged which deserve further investigations in a future. The ones we consider most relevant are the following:

- To extend DTB-MAC protocol by adding support for event-driven messages related to general safety applications in highway and urban scenarios.
- To extend our token-based protocols to handle the new additional challenges and problems, such as selecting a token manager when two tokens are detecting, or merging two platoons of cars driving in close proximity, thereby sharing the same channel for platooning information exchange.
- To build a real-world testbed for vehicular networks in order to perform experimental validation.
- To investigate other communication technologies, such as cellular networks, in order to propose hybrid vehicular networking protocols.

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Acronyms

ACK Acknowledgement. 11

ACs Access Categories. 20

AIFS Arbitrary IFS. 20

AODV Ad hoc On-Demand Distance Vector. 41

ARQ Automatic Repeat reQuest. 41

BDR Beacon Delivery Ratio. 59

BEB Binary Exponential Backoff. 11

BTHN Backup Token Holder Node. 52

C-ITS Cooperative ITS. 17

CanuMobiSim CANU Mobility Simulation Environment. 28

CCH Control Channel. 19

CORSIM CORridor SIMulation. 27

CS Channel State. 32

CSMA/CA Carrier Sense Multiple Access with Collision Avoidance. 10

CTS Clear-to-Send. 10

CW Contention Window. 11

DARPA US Defense Advanced Research Projects Agency. 26

DBM-ACW Density Based Method for Adjusting the CW size. 34

DDCWC Dynamic Deterministic Contention Window Control. 31

DIDD Double Increment Double Decrement. 13

DIFS Distributed coordination function IFS. 10

DN Dissociative Node. 52

DPBA Dynamic Priority Backoff Algorithm. 14

DSR Dynamic Source Routing. 41

DTB-MAC Dynamic Token Based MAC. 51

DYMO Dynamic MANET On-demand. 41

EDCA Enhanced Distributed Coordination Access. 19

EIED Exponential Increase Exponential Decrease. 13

ELBA Exponential Linear Backoff Algorithm. 14

FCR Fast Collision Resolution. 14

GloMoSim Global Mobile Information System Simulator. 26

GUI Graphical User Interface. 24

HBCWC History Based Contention Window Control. 31

IFS Inter Frame Space. 10

IP Internet Protocol. 29

IR Infra-Red. 23

IRT Inter-Reception Time. 81

iTetris Integrated Wireless and Traffic Platform for Real-Time Road Traffic Management Solutions. 29

ITS Intelligent Transportation Systems. 1

IWIS Integrated Wireless Intersection Simulator. 29

JiST Java in Simulation Time. 26

LILD Linear Increase Linear Decrease. 14

LMILD Linear/Multiplicative Increase and Linear Decrease. 13

MAC Medium Access Control. 2

MANET Mobile Ad hoc NETwork. 5

MCTRP Multi-Channel Token Ring MAC Protocol. 23

MILD Multiplication Increase Linear Decrease. 13

MOVE MObility model generator for VEhicular networks. 27

NAV Network Allocation Vector. 10
NCTUns National Chiao Tung University Network Simulation. 29
NS-2 Network Simulator 2. 26
NS-3 Network Simulator 3. 26

OBU On-Board Unit. 15
OFDM Orthogonal Frequency Division Multiplexing. 20
OLSR Optimized Link State Routing. 41
OTRP Overlay Token Ring Protocol. 22

PCB Pause-Count Backoff. 15
PCF Point Coordination Function. 10
PDR Packet Delivery Ratio. 37
PHY physical. 18
PIFS Point coordination function IFS. 10

QoS Quality of Service. 13

RMN Ring Member Node. 52
RSU Road Side Unit. 1
RTS Request-to-Send. 10

SCH Service Channel. 19
SDMA Space Division Multiple Access. 21
SDN Semi-Dissociative Node. 52
SIFS Short IFS. 10
SUMO Simulation Of Urban Mobility. 27
SWANS Scalable Wireless Ad hoc Network Simulator. 26

TCP Transmission Control Protocol. 28
TDMA Time Division Multiple Access. 21

THN	Token Holder Node. 52
TM	Token Manager. 72
TraNS	Traffic and Network Simulation Environment. 29
UDP	User Datagram Protocol. 41
V2I	vehicle-to-infrastructure. 15
V2V	Vehicle-to-Vehicle. 2
VANET	Vehicular Ad hoc NETwork. 4
Veins	Vehicles in Network Simulation. 28
VISSIM	Verkehr In Stadten SIMulationsmodell. 27
VsimRTI	V2X Simulation Runtime Infrastructure. 29
WAVE	Wireless Access in Vehicular Environment. 18
WDTP	Wireless Dynamic Token Protocol. 22
WTRP	Wireless Token Ring Protocol. 22