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DISSERTATION

DEPENDABLE MEDIUM ACCESS CONTROL FOR ROAD-TRAFFIC SAFETY

ausgeführt zum Zwecke der Erlangung des akademischen Grades eines
Doktors der technischen Wissenschaften

unter der Leitung von
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Lehenengo aitari, gero amari,
gero abuelo ta amamari,
ta azken orduan, ahaztu barik
Ondarruko familiari
("Salamankako kanta" doinuarekin kantatzeko)

Contents

Abstract

The IEEE802.11p is an approved amendment to the IEEE802.11 standard to add wireless access in vehicular environments (WAVE). It defines enhancements to the 802.11 required to support Cooperative Intelligent Transport Systems (C-ITS) applications. The IEEE802.11p MAC algorithm (namely EDCA) is CSMA-based using carrier sensing as method for monitoring the state of the channel before transmitting. In loaded vehicular ad-hoc networks (VANETs) the channel access delay of a vehicle attempting to access the channel increases unpredictably every time it is sensed busy. The Quality-of-Service (QoS) requirements demanded by safety-critical applications cannot be fulfilled. In contrast, Self-Organizing Time Division Multiple Access (SoTDMA) guarantees an upper bound on the channel access delay defined by the Selection Interval length (SI).

The European Telecommunications Standards Institute (ETSI) defines two types of safety-related messages: Cooperative Awareness Messages (CAMs) and Decentralized Environmental Notification Messages (DENMs). Both have periodic nature and each packet has a deadline to meet. In the United States CAMs are also known as Basic Set Messages (BSMs).

My research has focused on the field of vehicular communications. Initially on the evaluation of the performance of the standard MAC protocol in congested vehicular scenarios, where safety-related data is present and *transient congestion control* is required. Subsequently, the focus moved to the design of enhancements at the IEEE802.11p MAC layer so that dependability is assured for high-priority traffic, regardless of the vehicular traffic situation. The first step was building a simulation environment to compare the performance of different MAC protocols. My design of the MAC layer takes into account a self-managed and scalable communication environment. This work relates especially to safety-related applications, which may share real-time information and cooperate in an efficient, affordable and reliable way.

The next step was identifying challenging vehicular scenarios and defining new benchmarking metrics for evaluating the performance when scheduling traffic safety data. Finally, analytical expressions for validating the simulation tool are described for further design refinement.

The simulation results show that in high-density vehicle situations a congestion control method is required in order to provide reliability and robustness to safety-related communications. Although SoTDMA is proven to outperform plain EDCA in terms of predictability, it still fails to reach the selected relibility threshold set in this thesis, which requires that 90% of the generated safety messages are correctly decoded. In addition, the ETSI proposal for variable report rate is a drawback to the use of SoTDMA. Everytime the report rate is changed, a vehicle using SoTDMA enters the *initialization phase* and a message is dropped at the transmitter. This is unacceptable for safety-related data. My approach for achieving reliability is to design a suitable decentralized congestion control (DCC) mechanism on top of the pre-existing IEEE802.11p MAC. This work underlines the importance of a suitable parameter setting, namely the carrier sensing threshold (CST) value selection, so that reliability is achieved and sustained regardless of the traffic density. In this thesis, it is shown that the proposed multistate-active DCC mechanism achieves a robust and reliable performance when its parameters are properly selected.

Keywords: Cooperative intelligent transport systems, vehicular ad-hoc networks, medium access control, EDCA, SoTDMA, vehicle-to-vehicle communications, safety-related data, CAMs/BSMs, reliability, dependability, real-time communications, decentralized congestion control

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1

Vehicular Communications

Cooperative intelligent transport systems (C-ITS) enable new applications to be developed where data is exchanged wirelessly. In a cooperative system, nodes provide each other with information, such as safety warnings and traffic information. This can be used in order to avoid accidents and traffic congestions. The cooperation between vehicles for enhancing road traffic safety and efficiency will, in many cases, use vehicular *ad hoc* networks (VANETs) where all nodes are peers, vehicles as well as roadside units (RSUs). The *ad hoc* topology implies that there is no central coordination in the system such as a base station or access point controlling the network resources.

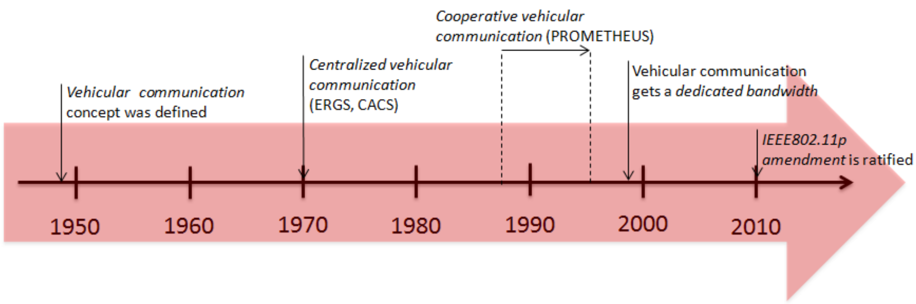

Figure 1.1: Brief chronology of Vehicular Communications

There has been extensive work on standardization to define a communication protocol for vehicular communications. The first approach was carried out by the Institute of Radio Engineers in New York, in December 1949. This contribution [4] describes the methodology of testing for railroad and vehicular communications.

Parameters such as test frequencies, test input signals, available power and standard input values (such as mean signal input, standard test modulation, sensitivity test input) were defined, and requirements and characteristics of testing apparatus and test procedures were introduced for the first time. In 1959, General Electric Company pointed out the "Shadows of the Future in Vehicular Communication". This work [5] affirms how the solid state revolution in electronic components meant much in the field of vehicular radio in terms of decreased size, lighter weight and greater efficiency. The contribution describes a slightly different use case for the vehicular communication as the actual C-ITS. The task of the vehicular station was to act as a repeater to maintain a satisfactory communication with the home base station. The main threat at this time for vehicular communications was the limit expansion. The improvements to be carried out thereupon were mainly in the field of channel space utilization, channel time utilization and equipment. In the 70th century in the USA an Electronic Route-Guidance System (ERGS) was proposed [6]. This in-vehicle navigation and route-guidance system was the precursor to Google's driverless car [7] . In Japan, the Agency of Industrial Science and Technology of the Ministry of International Trade and Industry (MITI) carried out the Comprehensive Automobile Traffic Control System (CACS) [8]. This communication system had a central computer control that coordinated the information from the vehicles collected at the RSUs, monitored the traffic flow and instructed individual drivers at each intersection which was the optimum route to take. In the 80th century, Europe entered the game with PROMETHEUS (Program for European Traffic with Highest Efficiency and Unprecedented Safety), where an inter-vehicle communication system was developed. Driverless vehicles achieved cooperative driving and were automatically tracked (platooning). From the 1990s to the present a transformation occurred with the appearance of 5.9 GHz DSRC (Dedicated Short-Range Communication). Then, three main research targets were started: communication architecture for cooperative systems, safety applications and key enabling technologies. Finally, in June 2010, the IEEE802.11p [9] was ratified, as an amendment to the IEEE802.11 wireless local area network (WLAN) standard. The major difference between the legacy 802.11 and 802.11p is the removal of the access point functionality in the latter. 802.11p uses carrier sense multiple access with collision avoidance (CSMA/CA) as medium access control (MAC) with support for quality of service (QoS) through 802.11e. The physical (PHY) layer of 802.11p, orthogonal frequency division multiplexing (OFDM), is inherited from 802.11a with the major difference that the frequency channel bandwidth is narrowed down to 10 MHz in 802.11p. In Europe a profile standard of IEEE802.11p has been approved by the European Telecommunication Standards Institute (ETSI), called ITS-G5 [10].

As stated in [11], the two lowest layers of the ETSI TC ITS protocol stack are almost identical to the wireless access in vehicular environments (WAVE) approach, with the exception that WAVE has the MAC-sublayer extension 1609.4 while ITS-G5 requires Decentralized Congestion Control (DCC) [12].

On one hand, in the field of physical layer, although WAVE (IEEE802.11p) is considered the standard for on-the-road communications, the International Organization for Standardization (ISO) under the framework Communication Architecture for Land Mobiles (CALM), the so called CALM M5, is contemplating the integration of several wireless technologies to provide seamless wireless communications for all end users. There has been a widespread research work in this field. [13] proposes the ZigBee standard [14], a low cost low power wireless networking standard for sensors and control devices, expected to be used in wireless sensor network applications where high data rates are not required. This work proposes the ZigBee technology to communicate vehicle and roadside units. The main drawbacks for using ZigBee for vehicular communications are the narrow coverage ranges, the narrow bandwidth and the *sleep mode* specified for low power consumption. Still, it might be a solution for intra-vehicle communication where ZigBee shall cater to Wireless Personal Area Network (WPAN). The use of wireless broadband access (e.g. Worldwide Interoperability for Microwave Access (WiMAX)) for vehicle to infrastructure is proposed in [15]. This contribution presents an optimization method for smart antenna use that exploits the characteristics of WiMAX technology to increase the coverage and throughput, hence reducing the infrastructure costs. And finally [16] and [17] draw a comparison between Universal Mobile Telecommunications System (UMTS) and Long Term Evolution (LTE) for vehicular networking. [16] shows how in comparison to DSRC, the cellular systems (3G) do not provide the same awareness update rate and latency at intersections as the dedicated 5.9 GHz IEEE802.11p communication. On the contrary, LTE seems to be able to perform well. [17] points out that during the initial phase of vehicular networks, LTE is expected to play a critical role in overcoming situations, where no 802.11p-equipped vehicles are within the transmission range. In addition, wide LTE coverage can be beneficially exploited for the reliable dissemination over large areas of event-triggered safety messages. But the question is how much the delivery of these messages via cellular system would cost in terms of money. This cost advantage pushes the IEEE802.11p forward over cellular communication.

On the other hand, in the field of MAC layer, to overcome limitations given by the vehicular propagation channels in roadway environments, [18] proposes an extension of the current method for improved QoS.

[19] presents a secure MAC protocol for VANETs with different message priorities for different types of applications, focusing more its effort on improving security and data integrity rather than in time critical message delivery. It is in [20], where a deeper study of the delays introduced by the actual IEEE802.11p MAC layer protocol is carried out. Results show how analyzing the delay dependencies on different loads (in Mbps) is a matter of interest. All the solutions and studies presented so far, have worked with collision avoidance medium access algorithms, where nodes adopt a handshaking approach before sending messages. But there are also alternative MAC approaches, time-slotted based and adapted to the VANET environment. [21–27] stem from Slotted Aloha (S-Aloha), which was proposed in 1975 in [28]. These time-slotted approaches have two main drawbacks: (1) cannot handle scalability in overloaded situations and (2) slot allocation as perceived by a particular node is not distributed amongst the neighbours. In 2009 the work of [29] took Time Division Multiple Access (TDMA) into account, as another possible collision avoidance MAC method for vehicular environments. TDMA [30] is a technique where the timeline is split into a series of the time periods, and each period is divided into a set of time slots. Each vehicle is then assigned a slot in which it transmits its messages every period. As vehicular networks have a dynamic topology, the slot assignment must be validated as changes happen, in order to keep the MAC layer protocol mobility-aware. This proposal, known as Self-Organizing Time Division Multiple Access (SoTDMA), overcomes the two aforementioned inconveniences for time-slotted approaches. Later in 2010, reference [31] also presented another TDMA solution for RSU-to-vehicle communication. This approach consists of a sublayer to be on-top of the conventional IEEE802.11p MAC. The solution presented shows to be plausible for RSU-to-vehicle communication scenarios but not in a vehicle-to-vehicle communication context, where the extension of the coverage area is not as important as a predictable and a low delay on the transmissions.

In order to evaluate the performance of the underlying technology, it is important to define the application it provides access to. The requirements for a safety application, which has to meet a hard deadline are not the same as the ones for a file sharing application. New kind of applications such as e-safety, traffic management, enhanced driver comfort and vehicle maintenance applications, lead to new communication scenarios in vehicular environments. Road traffic safety applications are the ones with the strongest requirements on the communication. For example sending *emergency notifications* requires a low channel access delay, in order to notify relevant receivers on time to avoid collisions; for *risk anticipation* the key feature is predictable channel access delay. Vehicles are monitored so abnormal behaviors can be detected and any change on the cadence of the data traffic must be tracked.

ETSI has defined two types of messages for safety-related applications, namely cooperative awareness messages (CAMs) [32] and decentralized environmental notification messages (DENMs) [33]. CAMs are broadcasted periodically, with an update rate of 1-10 Hz depending on the context and contain position, speed, heading of the vehicle; they are time-triggered and always present. They will be 200 bytes long, plus security overhead to be added. DENMs, on the other hand, are event-driven and will be triggered when a dangerous situation is about to happen. USA does not have a distinct name for event-driven type of messages, but time-triggered messages are called basic safety messages (BSMs). Both message types require predictability, whereas CAMs/BSMs have modest reliability requirements and DENMs have superior reliability requirements. By predictability is meant that the MAC layers should have a known maximum delay, such that a message can be delivered to the receiver before a predefined deadline. The MAC layer protocol for scheduling safety-related data traffic must be predictable, self-organizing and support both event-driven and time-triggered data traffic.

In such communication scenario where e-safety periodic data traffic is present and the IEEE802.11p is the key enabling technology, the aforesaid scalability is an open issue. One way to handle it via MAC algorithms, such as CSMA/CA and S-Aloha, is the control theory approach. This theory deals with the behavior of dynamic systems with an external input, called the reference. Given that one or more output variables of the system need to follow a certain reference over time, a controller manipulates the inputs to the system to obtain the desired effect on the output. For safety-related applications in VANETs, when a dense traffic situation is detected, the so called ”controller” will make a decision and take an action so that the MAC behavior is dependable. In the field of medium access control, dependability is a measure of a systems availability (i.e. readiness for correct service) and reliability (i.e. continuity for correct service). In a cooperative networking scenario, it is possible to get feedback (i.e. external input) from neighboring nodes of the VANET; that is known as closed-loop controller. If this feedback is first-order feedback with respect to the desired result, it is called explicit feedback. Whereas if the observations are correlated with the relevant measure, it will be implicit feedback. Focusing on the congestion control, the aim is to provide a harmonized and fair access to the channel. This means limiting the load of a subset of the users either by limiting the transmit power, packet generation rate or changing some of the thresholds in the communications which affect the channel load. This will be the function of the DCC, a cross-layer mechanism that varies the parameter setting of the PHY layer (such as transmit power, packet transmission interval, carrier sensing threshold or modulation and coding scheme) based on a reference measured in the MAC layer (such as channel busy ratio, CBR).

Congestion control can be classified as reactive or proactive. Reactive congestion control has first-order feedback about the channel state and reacts based on that value compared to a threshold. Proactive congestion control has a built-in model about the environment and tries to estimate the traffic in the next time instant a.k.a control period. There have been different partial solutions for congestion control: [34] uses a proactive open-loop controller (no feedback and built-in model for traffic estimation) and suggests a multiplicative decreasing rate algorithm for packet generation rate in case of emergency. [35] presents a reactive closed-loop controller (with first-order feedback) and since nodes are not synchronized, it can lead to adjustment oscillations; to achieve fairness neighboring nodes exchange their CBR measurements. [36] combines a proactive and reactive scheme, where nodes set the packet generation rate based on the predicted error of its own position by neighboring nodes and the transmission power based on the measures of the channel busy time. The most prominent proposal for handling scalability through transmit power control (TPC) is found in [37]. It presents a distributed fair power adjustment for vehicular environments (D-FPAV), designed to achieve congestion control, fairness and prioritization. The algorithm is periodically executed to follow channel and vehicular traffic changes. First it gathers information about the neighbour nodes, then locally solves the so called congestion control under fairness constraints (CCF) problem, thirdly computed values are exchanged amongst the neighbours and finally a minimum power value is selected. The computed solution is rarely the optimum as the carrier sense ranges are generally not symmetric and it is usually larger than the transmission range. Thus a multi-hopping strategy has to be utilized, which leads to considerable overhead in the communication. Finally [38] presents a congestion management approach through transmit rate control (TRC). The goal of this algorithm is again controlling the channel load via aggregate message rate. A target aggregate rate is defined, then the current aggregate rate is calculated and finally the linear message rate integrated control (LIMERIC) tries to adapt both linearly. The idealized case uses the aggregate offered rate which is practically very difficult to know. CBR is, on the contrary, easy to measure. LIMERIC uses an open-loop controller. For becoming a closed-loop controller, the current way under research is adopting PULSAR [39] information sharing protocol approach for LIMERIC by using distributed feedback information.

The goal of this thesis is to evaluate the performance of different MAC schemes for vehicular communications. The scope focuses on the subject of the communication requirements for safety-related applications under the constraints of the C-ITS communication standard. Therefore, this work investigates the IEEE802.11p MAC and SoTDMA.

The first simulations validate SoTDMA performance using measurement-based SNR time-series as PHY layer curves. The following simulations compare both MAC methods. Whereas the work of [11] studied a steady-state scenario (fixed high traffic density) where periodic position messages (CAMs/BSMs) are present on a six lanes in each direction highway scenario, this thesis evaluates two transient-state scenarios (variable high traffic density): (1) a *start-up scenario*, where a large number of vehicles are started simultaneously and try to access the medium, and (2) a *two VANETs merging scenario*, where two VANETs driving in opposite directions merge on a highway with six lanes in each direction. On top of that, this work also evaluates the performance of the latest MAC layer enhancement proposed, the DCC mechanism and proposes a multistate active DCC solution. And to sum up, suitable performance indicators are also defined for each scenario.

The following research questions have been addressed in this thesis:

1. Does the alternative MAC scheme, SoTDMA, perform reliably in real vehicular scenarios?

2. Which are the challenging vehicular scenarios for MAC schemes broadcasting road traffic safety data?

3. Which performance metrics are suitable for evaluating MAC schemes for road traffic applications in those vehicular scenarios?

4. Can the new crosslayer enhancement, the DCC mechanism, cope with the scalability issues given the traffic-safety data pattern?

5. What is the impact of parametrization in the performance of the DCC mechanism?

6. What is the impact of parametrization in the performance of SoTDMA?

The research presented in this thesis started in 2010. First steps into dependable vehicular communications were taken in the field of the physical layer. The contribution [40] studied the availability of Ricean multiple-input-multiple-output (MIMO) channels. Results show that MIMO channels with higher spatial correlation lead to lower ergodic capacity and critical data rate. [41] presented the results of reliability in terms of temporal evolution of ergodic capacity and critical data rate. The channel with strongest line-of-sight (LoS) component also has the highest capacity. At this point it was clear that the ability of readiness and continuity for correct service does not only depend on the physical layer but also on the upper layer: the MAC layer (in charge of providing channel access control mechanisms that make it possible for several vehicles to communicate within a multiple access network that incorporates a shared medium). Thanks to the work [29], SoTDMA stood out as a suitable alternative MAC scheme for scheduling safety-related data traffic. After implementing a simplified SoTDMA MAC simulator in Simulink, and making use of the measurement data retrieved from the ROADSAFE 2011 measurement campaign [42], the contribution [1] presented the time evolution of throughput based on measured SNR time-series of four vehicles driving on the same road joining the channel. Results validate the collision-free access and predictability of SoTDMA in real-world scenarios. In order to compare and contrast the performance of both MAC schemes, IEEE802.11p MAC and SoTDMA, and due to the lack of a PHY-MAC-NET simulator that implemented both algorithms, in 2012 full PHY-MAC simulators were implemented in Matlab. In addition challenging vehicular scenarios were identified, namely those where traffic density was high and variable. The first results on *start-up phase VANETs* were shown in [2], where the stabilization time (i.e. the time required to perform reliably) of CSMA/CA and SoTDMA is compared for different channel loads. And it has been during 2013 when a complete evaluation study of the DCC mechanism has been carried out. Different DCC designs have been simulated and the impact of carrier sensing threshold (CST) has been studied on a *two VANETs merging scenario*. At last, a final design for the DCC mechanism is proposed, as well as a CST value for fulfilling the requirements imposed on the MAC layer for VANETs used for broadcasting road traffic safety data (i.e. providing reliability and dependability).

The major contributions of this thesis are

1. Validating SoTDMA MAC scheme performance using measurement-based time-series as PHY layer

2. Identifying variable traffic density scenarios for road traffic safety applications

3. New performance measures for evaluating both MAC schemes, the current standard IEEE802.11p and SoTDMA

4. Proposal of using multistate active DCC mechanisms for VANETs

5. Evaluation the impact of parametrization in the performance of the DCC mechanism

6. Evaluating the impact of parametrization in the performance of SoTDMA

The research presented in this work has also contributed to the COST-IC1004 action, with several non-peer reviewed articles.

The methodology used is described in Figure 1.2. The analytical model consist of a description of the collision probability of both MAC methods using mathematical concepts. Simulation is the imitation of the operation of a real-world system over time in the aforementioned scenarios. Simulation results have been used for ratifying the analytical model in the *start-up phase of a VANET scenario*. In this work simulation step's modus operandi is the following: first a literature study is carried out and a problem is identified; performance metrics are afterwards defined and finally MAC methods are implemented and extensive computer simulations are executed.

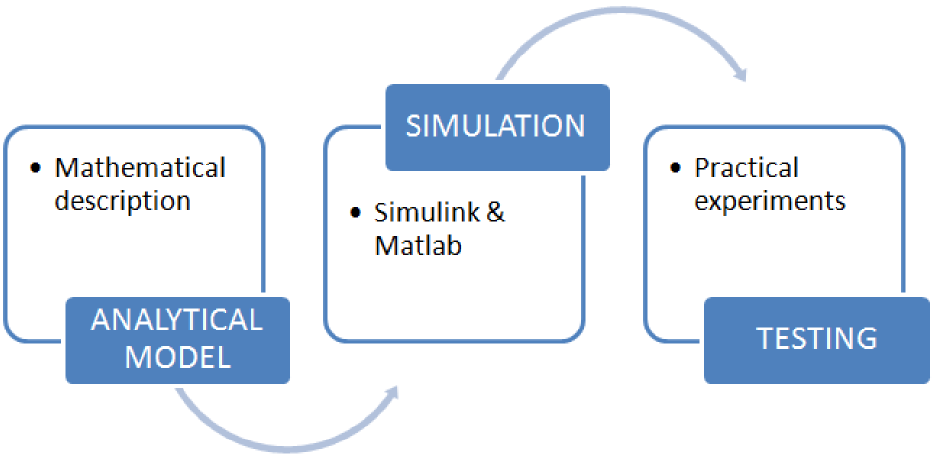

Figure 1.2: Methodology Outline

The third step of the method would be testing. In the particular situation of this thesis, where high traffic density scenarios have been analyzed, this last step has been impracticable due to the size of the VANET (up to 400 vehicles) and the lack of equipment. Nonetheless, results could be corroborated by testing. This could provide information about the quality of the system and would help appreciating and understanding the risks of implementation.

2

Medium Access Control (MAC) Layer

This chapter presents the key features of the IEEE802.11p MAC for vehicular communications in terms of architecture, MAC parameter settings, collision nature and MAC protocol data unit (MPDU) format. It also describes the operation of the algorithm and presents the main drawbacks when it comes to using the IEEE802.11p MAC for scheduling safety-related data. A very detailed description of the medium access control for VANETs is to be found in [11], where all the stack layers involved are throughly explained.

The IEEE802.11-2012 MAC architecture can be defined as providing point coordination function (PCF) or hybrid coordination function (HCF) through the services of distributed coordination function (DCF). DCF is a CSMA/CA algorithm. Due to the peer-to-peer architecture of VANETs, the MAC architecture deployed by IEEE802.11p is the enhanced distributed coordination function (EDCA). It is based on the basic DCF and adds QoS attributes. EDCA defines four different priority queues or access categories (AC), each with different values of arbitrary interframe space (AIFSN) and back-off range: AC Voice (AC VO), AC Video (AC VI), AC Best Effort (AC BE) and AC Background (AC BA). Safety-related data is either AC VO ($CW_{min} = 3$, $CW_{max} = 7$, $AIFSN = 2$) or AC VI ($CW_{min} = 7$, $CW_{max} = 15$, $AIFSN = 3$). The contention window limits, CW_{min} and CW_{max}, from which the random back-off is computed depend on the AC. The $AIFS(AC)$ is defined as,

$$AIFS(AC) = AIFSN(N) \cdot aSlotTime + aSIFSTime, \tag{2.1}$$

where aSIFSTime stands for short interframe period, a small time interval between the frame and the acknowledgment. For the IEEE802.11p the OFDM PHY layer parameter values aSlotTime and aSIFSTime are set to 13 us and 32 us respectively. And N stands for the maximum number of transmissions attempts of a message. The back-off duration is calculated as,

$$T_{back-off} = value_{rnd_{back-off}} \cdot aSlotTime. \tag{2.2}$$

The MAC sub-layer also contains the IEEE Std.1609.4-2010, which deals with multi-channel operation. As stated in [11], there are seven predetermined frequency channels - one control channel (CCH) and six service channels (SCH). IP-based data traffic is only allowed on SCHs, whereas non-IP-based data traffic can be transmitted in both CCH and SCHs. The basic idea within channel switching strategy is to use the CCH interval in the beginning of every 100ms interval for enabling vehicles to find each other. During the SCH interval vehicles can decide to either switch to a SCH annonced during the CCH interval or not. The original plan was to use the CCH for transmitting the time-triggered CAM messages. However, with the proposed channel switching strategy only 50% of the time is available for CAM transmissions and it is mandatory to listen to the CCH during the CCH interval. With many vehicles in the system sending with an update rate of 10 Hz, not everyone would fit into the CCH interval. Therefore, a consensus has been reached is U.S. to the use SCH channel number 172 for CAM/BSM transmissions (with no channel switching).

Eventhough IEEE802.11p MAC implements collision avoidance (based on the channel sensing before transmitting), real collisions still happen if two vehicles sense the channel idle simultaneously and attempt to access it at the same time. In addition, apart from real collisions that involve queues from different stations, the usage of EDCA introduces a new kind of collisions, so called *virtual collisions* [43]. *Virtual collisions* involve two queues belonging to the same transmitting station. If the back-off procedures of several different queues within the same vehicle finish at the same time-slot, the queue with the highest priority has the right to be the first to try to access the medium. The other will behave as if a real collision ocurred, meaning that their contention window is doubled within the contention window range. That will possibly delay its next trial to access the medium. Therefore, this statement makes clear that if in order to prioritize DENM messages to CAMs within the same station, DENMs have to be assigned a higher priority: Hence, virtual collisions amongst CAMs and DENMs might happen and this may affect the system performance.

The MAC protocol adds a header and a trailer to the incoming packet from the higher layer and defines the MPDU. *Frame control* contains information about protocol version, type of frame being transmitted and if the frame is fragmented or not. The *duration field* contains the packet duration. The four consequent fields are dedicated to *addressing*. And last *sequence control* keeps track of the packets by numbering them and it also states if the packet is fragmented or not. The *QoS control* contains as information about quality service. Finally, the *trailer* is a frame check sequence (FCS) being a 32-bit cyclic redundancy check (CRC).

2.1 Operation of the Enhanced Distributed Channel Access (EDCA) algorithm

The IEEE802.11p MAC channel access procedure of *a vehicle in unicast mode* starts by listening to the channel before transmission and if the channel activity is perceived as idle for a predetermined listening period, the vehicle starts transmiting directly. If the channel is or becomes occupied during the listening period, the vehicle performs a back-off procedure , i.e. it has to defer its access a randomized time period ($T_{back-off}$). The Contention Window (CW) is then set to the minimum Contention Window size (CW_{min}). And a back-off value ($value_{rnd_{back-off}}$) is randomly selected [0,CW]. The back-off counter is decremented everytime the channel is sensed free for AIFS time, until the back-off counter expires and the message is transmitted. Still the unicast transmission is not completed until a successful reception of the acknowledgement (ACK) is achieved. On one hand, if the ACK is not successfully received a maximum number of transmissions attempts are defined for each message. If this number is not reached and CW is not larger as CW_{max}, CW_{new} value is increased. If it has already scored CW_{max}, CW_{new} is set to CW_{max}, and a new back-off value is randomly drawn [0,CW_{new}]. On the other hand, if the maximum number of transmissions attempts are achieved without receiving the ACK, the transmission is said to be failed.

The channel access procedure of *a vehicle in broadcast mode* waits for no ACK. It also starts by listening to the channel before transmiting and if the channel activity is perceived as idle for a AIFS period, the vehicle can start transmiting directly. If the channel is or becomes occupied during the listening period, the vehicle must perform a back-off procedure. The CW is then set to the minimum Contention Window size (CW_{min}). And a back-off value is randomly drawn [0,CW]. The back-off counter is decremented everytime the channel is sensed idle for AIFS time until the back-off counter expires and the message is transmitted.

In the broadcast mode there is no exponential increase of the CW size as the back-off procedure is only invoked during initial sensing of the channel.

Each message entering the MAC layer has a related lifetime counter, defining the time its information is valid. When this lifetime counter is exceeded, the message is discarded. On top of that, as before mentioned, in the unicast mode the messages which ACK reception is unsuccessful are also dropped. When this happens all the CW parameters will be restarted for the new message. Message drops are very dangerous specially when traffic safety data is scheduled. These message drops are translated into priority information losses, that may lead to a dangerous situation. Apart from the drops, when EDCA is used in a VANET relaying in the IEEE802.11p PHY, where vehicles do not have full connectivity to all other neighbours, the EDCA is no longer predictable and transmissions can start simultaneously due to hidden terminals.

2.2 Criticism of IEEE802.11p MAC

A VANET is a challenging network for the IEEE802.11p MAC protocol because the number of nodes is unknown and cannot be bound. Therefore scalability and fairness problems [44] arise in dense vehicle traffic situations and have a major influence on the performance of the MAC method in cooperative ITS. When using EDCA, the channel access delay is not upper-bounded and it is unknown until transmissions begins, as it is based on the instantaneous channel load and vehicles can experience a random delay when they back-off.

Not only the communication scenario but also the nature and requirements of safety-related data traffic have an impact on the performance of EDCA. This MAC method was originally thought for scheduling best-effort unicast data traffic. The goal in this situation was to avoid collisions regardless of the delay and for that purpose, channel access is randomized. In the case of traffic safety-related data, the requirements on the delay are to keep it low and predictable, as these messages are most valuable the sooner they are scheduled. And on the coverage range, safety-related messages are one-hop, so it is important that they are spread as far as possible, so that distant neighbours can react on-time. IEEE802.11p MAC only provides low delay under sparse traffic situation, when the channel access probability is high. But as the vehicle density increases the MAC performance becomes unpredictable and the delay increases. So, the QoS restrictions related to traffic safety-related applications cannot be fullfilled and the overall VANET performance becomes unreliable.

In addition, a reliable performance must not only be achieved but maintained, regardless of the variable traffic situation. Results will show that the plain IEEE802.11p MAC protocol is not robust to vehicular traffic density changes.

3

Enhancements on the 11p MAC Layer

The main drawback of the IEEE802.11p MAC is the performance when the channel is heavily loaded or the channel load changes abruptly. The carrier sensing procedure before sending is translated into too long waiting times for the safety message to fulfill its warning purpose. For safety-related messages, which are sent periodically it is critical that they are sent on-time so that actions can be taken early enough to avoid risky situations.

There are two ways to go in order to ensure a dependable behaviour of the MAC layer for vehicular communications: (1) proposing a new MAC standard to be inherited by the IEEE802.11p standard MAC or (2) implementing enhancements on top of the standard. One example of the earlier solution is the SoTDMA MAC layer algorithm and of the latter the DCC mechanism.

3.1 Self-Organizing Time Division Multiple Access (SoTDMA) MAC Layer Algorithm

The *Self-Organizing Time Division Multiple Access (SoTDMA)* MAC method was originated for the ship industry. It provides a structured access to the channel. It divides the channel in N_{FS} time-slots. If m messages per frame are transmitted, the frame is divided into m subframes, that are $N_{NI} = N_{FS}/m$ time-slot long. These subframes are called Nominal Increments (NI).

When a vehicle wants to allocate a time-slot for transmission, it first listens to the whole frame structure (*Initialization Phase*).

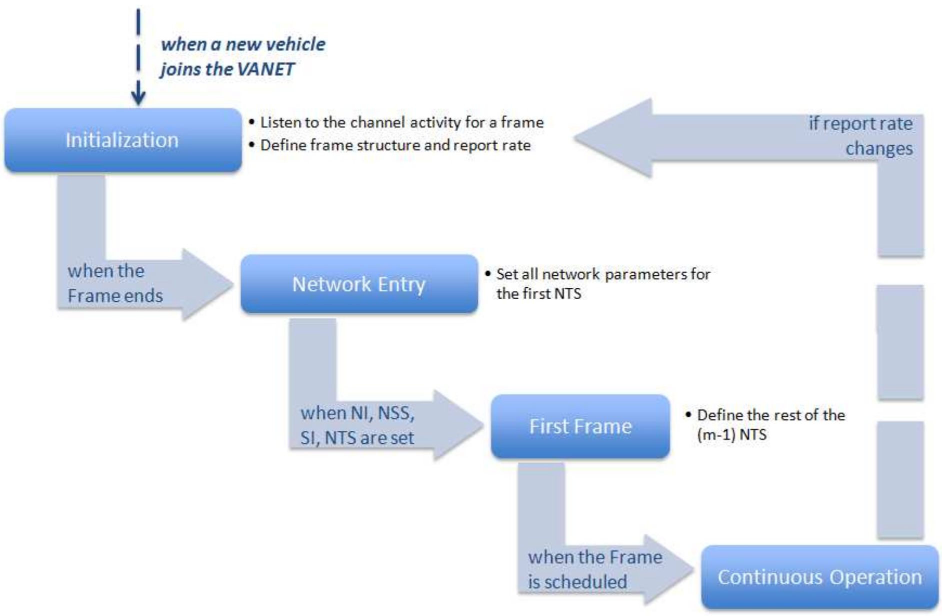

Figure 3.1: Flow chart of the SoTDMA MAC Protocol

Then it enters the *Network Entry Phase*, where the first time-slot is scheduled. The vehicle chooses a random number, the Nominal Selection Slot (NSS), between 1 and NI. A $N_{SI} = N_{NI} \cdot 0.2$ amount of time-slots are symmetrically distributed around the NSS. This subgroup of time-slots is called Selection Interval (SI). The Nominal Transmission Slot (NTS) is then selected out of the available time-slots of the SI. If the SI is full, the vehicle will select the transmission slot of its furthest located neighbour. During the *First Frame Phase* this is repeated for each NI, locating the Nominal Slot (NS) as NS=NSS+NI, and repeating the same procedure as in the first NI until all the m messages are scheduled. The next phase is called *Continuous Operation*, where the vehicle keeps using the allocated positions until their n parameters expire. Each NTS has an n parameter related to it, which defines the number of consecutive frames in which this time-slot will be used by the vehicle.

When it expires, another available time-slot out of the SI is selected (or if the frame is full the time-slot of the furthest away located neighbour).

3.2 Decentralized Congestion Control (DCC) mechanism

ETSI has proposed a *Decentralized Congestion Control (DCC)* scheme in order to mitigate the IEEE802.11p MAC layer congestion issues at high vehicle densities. The DCC mechanism [45] is based on an underlying state machine where the transmit parameters are chosen, based on the observed channel load. It does not require changes in the existing PHY/MAC standards as defined in IEEE802.11p [9].

The main goal of the DCC is to ease the channel load (CL), so that safety data traffic can be served on-time. It is a crosslayer solution because based on a MAC layer performance indicator, PHY layer parameters are set in order to enhance the IEEE802.11p performance. The transmission parameters associated with a certain state include transmit power (P), packet transmission interval (PI), CST and coding schemes (MCS) among other parameters. The CL is defined to be the fraction of time where received power was greater than the CST. The ETSI standard foresees several active states, but leaves the framework open for implementation.

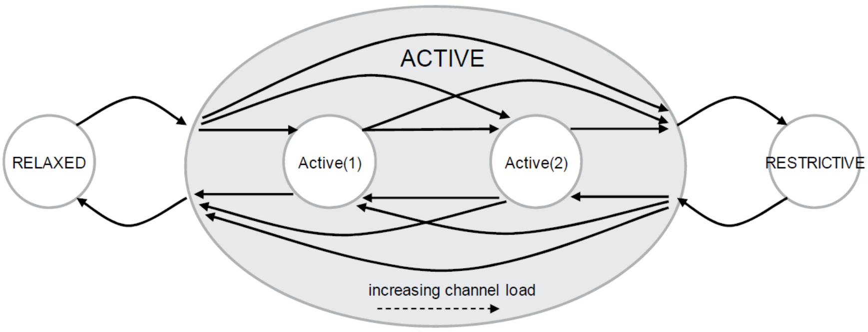

Figure 3.2: Currently proposed DCC Mechanism: The state machine proposed by ETSI DCC framework (ETSI TS 102 687 V1.1.1 (2011-07))

4

Definition of Performance Indicators

Performance evaluation is a method by which the job performance of a system/device is measured. First the most meaningful performance features of the service to be provided have to be identified. Then an indicator which records the evolution of those features is selected or defined. And finally the analysis is carried out.

The system under test is the MAC algorithm, in particular when scheduling safety-related data traffic. Is very important to underline the nature of the data, because the data traffic features and requirements are associated to its performance. The requirements of a MAC algorithm working with best-effort unicast traffic are not the same as if that MAC algorithm deals with real-time broadcast traffic. The restrictions applied to the first case in order to schedule efficiently are more permissive than the ones to be applied to the latter case. Safety-related applications broadcast periodic messages, which have a certain deadline to meet, so a suitable MAC algorithm must have a predictable behaviour and provide low channel access delays.

Not only the data traffic nature has to be taken into account, but also the content or the aim of the information being transmited. E-safety data has the aim to inform the traffic in the vicinity about an occurrence, either by just making the neighbour vehicles aware of the reference vehicle or by warning them about an emergency situation so the can anticipate to it. Therefore the dissemination of the information is a key factor, hand in hand with the timely warning.

The most popular performance indicator to evaluate MAC performance is the *throughput*, defined in Section 4.1. It is useful if the data rate or the message size are variable, to see the amount of information that is actually being successful. But in the case of safety-related information, it is only useful for validation purposes, as used in [1], because both, message size and data rate, are constant. *Probability of packet reception (PPR)* is a useful performance indicator, because it gives a taste of the dissemination of an individual transmission. But it does not provide a global view of the QoS. The *cumulative distribution function (CDF) of the MAC-to-MAC delay*, specified by [11], is a suitable reliability indicator for the purpose in terms of delay. But only using this, the dissemination information would be missing, i.e. a suitable reliability indicator in terms of coverage range.

Performance Indicator	Suitability	Why?
Throughput	Inappropriate – maybe for validation but not for performance evaluation	*Safety-related data traffic* consists of short periodic messages exchange amongst peers (fix data rate and message size)
Probability of Packet Reception	Appropriate	It is a dissemination indicator with respect to Tx-Rx distance
CDF of MAC-to-MAC delay	Appropriate – reliability in terms of delay	Useful to have a look at the *delay-related performance*, which is a key feature for safety-related messages. It can be monitored throughout the simulation time
CCDF Coverage range for a certain QoS *(PPR, Deadline MAC-to-MAC delay)*	Appropriate – reliability in terms of coverage range	It is a *QoS (Quality of Service)* indicator. It shows the coverage range achieved by a transmitter and its reliability
Stabilization Time *(Deadline MAC-to-MAC delay)*	Appropriate – but only for variable traffic density scenarios	Only suitable for *transient state of a VANET* analysis
Freshness of Information	Appropriate	*Safety-related data* is most useful when is most updated. This parameter evaluates transmit rate control scheme performance
Probability of collision	Appropriate	Describes the performance of the MAC protocol under initial certain circumstances

Figure 4.1: Suitability evaluation of different performance indicators for analyzing MAC conduct when scheduling safety-related data

With that in mind the author has defined the *complementary cumulative distribution function (CCDF) of coverage range* in Section 4.5. To the author's knowledge, this was the missing piece of the tuple $(\Delta t, \Delta d)$. Section 4.6 determines a performance indicator for evaluating TRC performance and lastly collision probability is specified for both, IEEE802.11p MAC and SoTDMA, for sake of validation of the self-developed simulation tool (based on previous work of [46]).

4.1 Throughput

It is defined as the average rate of successful message delivery over a communication channel. This data may be conveyed over a physical or logical link through a certain network node. The throughput is usually measured in bits per second (bps).

$$Thr_{aggregate} = N_{bits/packet} \cdot P_{packet/frame} \cdot t_{seconds/frame} \tag{4.1}$$

The system throughput or aggregate throughput is the sum of the data rates that are delivered to all terminals in a network.

4.2 Probability of Packet Reception (PPR)

The Probability of Packet Reception (PPR) is defined as the percentage of nodes that receive a broadcasted message from a source. The aim is to provide a reliable broadcast in terms of ensuring it to be larger than a threshold ($PPR > PPR_{th}$).

4.3 Cumulative Distribution Function (CDF) of MAC-to-MAC Delay

For each broadcasted message by the node under study all the received and loss messages are analyzed. Their MAC-to-MAC delays are evaluated, where MAC-to-MAC delay consists of channel access delay, propagation delay and decoding delay. This performance indicator reflects the reliability of a transmission in terms of delay, i.e. in terms of percentage how many of all broadcasted packets have arrived within a certain deadline.

The results will be shown as the CDF of the MAC-to-MAC delay. CDF describes the probability that a real-valued random variable (e.g. MAC-to-MAC delay) with a given probability distribution is found at less than or equal to x (e.g. for safety-related data the deadline is defined as 100 ms)

$$F_{\tau_{MM}}(\tau_{dl}) = P(\tau_{MM} \leq \tau_{dl}) \tag{4.2}$$

4.4 Stabilization Time

Safety-related data needs to meet a hard deadline (i.e. there are penalties or costs associated with missing the deadline). Here, the author defines two states: *State (0)*:= *poor* MAC performance and *State (1)*:= *good* MAC performance. Specifically, MAC performance is *good* if at least 90% of all generated packets have a MAC-to-MAC delay $\leq$ 100 ms otherwise the MAC performance is *poor*. This 90% threshold has been selected after concluding from [47] that for safety-related data 85% is not good enough. Industrial partners from the automotive industry have supported author's choice. The *stabilization time* t_{stab} is defined as the duration required for reaching a reliable performance, i.e. the duration required to achieve *good* MAC performance and keep it consistently until the end of the simulation time ((t_{stab}:end)). It is useful to evaluate the performance in transient scenarios, e.g. when the VANET is initialized or when the vehicle traffic density changes in time.

$$t_{stab} \Rightarrow F'_{\tau_{MM}}(\tau_{dl}) = P(\tau_{MM}(t_{stab} : end) \leq \tau_{dl}) \geq 90\% \tag{4.3}$$

4.5 Complementary Cumulative Distribution Function (CCDF) of Coverage Range in time

For each broadcasted message by an individual node the maximum transmitter-receiver distance is defined as the coverage range. This performance indicator defines the probability of reaching a furthest away distance achieved by a broadcast per channel realization (frame), e.g. the dissemination range. It provides a sense of the reliability in terms of coverage range.

The performance indicator used for evaluation in this contribution is coverage range where a certain QoS is provided. This QoS is determined by the PPR and a certain deadline. *Awareness coverage range (PPR, Deadline (ms))=(*0.75, 500*)* defines the range achieved by lower QoS (i.e. with a more permissive parameter setting), whereas *emergency coverage range (PPR, Deadline (ms))=(*0.9, 100*)* defines the dissemination range for more restrictive parameter setting.

A transmitter broadcasts its priority messages $\mathbf{x}_n(t)$. For each of n transmissions (where $1 < n < R$) there are $R-1$ received packets. The MAC algorithm at the transmitter causes a delay τ by sensing the channel and waiting for transmission. An on-time scheduled priority message will be transmitted before the 100 ms deadline. Then the probability of PPR of the transmitted package according to the used channel model.

Coverage range for one transmission at time t is defined as,

$$\delta_t = \max_{1 \leq r \leq R} | \mathbf{x}_n(t) - \mathbf{y}_r(t + \tau)|, \tag{4.4}$$

where PPR is set and a deadline on the MAC-to-MAC delay $\tau < \tau_{max}$ is defined depending on the priority of the traffic.
Then a set of distances is defined for each transmitter, i.e.,

$$D = \{\delta_1, \delta_5, \delta_2 0, ...\delta_{n\delta}\}. \tag{4.5}$$

Finally, applying the CCDF of D, the probability of coverage range versus distance to the transmitter in meters is obtained.

4.6 Freshness of the Safety Information present in the VANET

This performance indicator is defined in order to evaluate different transmit rate control algorithms. By freshness in meant the "age" of the messages (validity time, since it is generated at the transmitter until it is discarded at the receiver) present in the VANET and its evolution in time.

For safety-related data it is very important that the broadcasted data is as contemporary as possible, i.e. the transmissions are most up-to-date. The *fresher* the information is, the more relevant it is. And as results will show, variable message generation rate introduces a great enhancement by these means.

4.7 Probability of collision for IEEE802.11p MAC and SoTDMA

As defined in Chapter 2, in the vehicular environments where safety messages are broadcasted, a collision amongst transmitting vehicles may occur. Depending on the geographical situation of the vehicles, simultaneous transmissions lead to:

a. Receiver collisions if any receiving vehicles can not correctly decode either of the messages

b. Correct receptions if any receiving vehicle can correctly decode either of the messages

A vehicle may experience a transmitter collision,

- With vehicles out of its coverage range (non-neighbour vehicles), or
- With vehicles within its coverage range (neighbour vehicles).

To obtain the expression of (transmitter) collision probability ($P_{collision}$) for EDCA and SoTDMA, several parameters have to be determined:

- Neighbour vehicles (V_q) for EDCA, are the ones which lie within the range defined by the CST. Whereas for SoTDMA, V_q are the number of vehicles that lie within the signal to interference plus noise ratio (SINR) threshold range.
- A structured channel is assumed, which consists of N_{FS} time-slots, for both MAC protocols, where a time-slot is a MAC packet long. This structure can be assumed as the only traffic present is safety-related periodic data traffic with constant MAC packet length.

Table 4.1: Parameters for deriving $P_{collision}$ for EDCA and SoTDMA

Parameters	Description
V	Total number of vehicles
V_q	Number of neighbour vehicles
$V_{q'} \in V_q$	Number of neighbour vehicles in contention phase
$V - V_q$	Number of non-neighbour vehicles
$V_k \in V_q$	Number of non-neighbour vehicles in contention phase
N_{FS}	Number of time-slots per frame
N_{NI}	Number of time-slots per NI
l	The index of NIs assigned to *vehicle i*
N_{SI}	Number of time-slots within the SI
n_q	Number of NTS assigned to q neighbour vehicles
$n_{q'} \in n_q$	Number of NTS assigned to q neighbour within the SI
$n_{q''} \in n_q$	Number of NTS assigned to q neighbour within the M
n_{CW}	Number of time-slots of the contention window
n_N	Number of consecutive frames using the same NS

When using EDCA as MAC protocol, *vehicle i* may experience (transmitter) collision with vehicles out of its coverage range which can either be in contention phase or not in contention phase. $P_{collisionOut}$ for *vehicle i* can be determined for the whole frame by summing over all the selection ranges,

$$P_{collisionOut} = \frac{N_{NI}}{N_{NF}} \sum_{l=1}^{\frac{N_{NF}}{N_{NI}}} \left[P_{collisionNotContendingOut} + P_{collisionContendingOut} \right] \tag{4.6}$$

1. A (transmitter) collision between *vehicle i* and not contending out-of-range vehicles may take place when any of those $V - V_q - V_k$ non-neighbour vehicles select to transmit anytime, excluding the transmission times where the channel is sensed busy (whose number can be expressed as $N_{NI} - n_q$). Assuming that the probability of an *out-of-range vehicle j* selecting a time-slot among available time slots is equiprobable, it can be calculated

$$P_{collisionNotContendingOut} = \sum_{j=1}^{V-V_q-V_k} P(X_i = X_j) = \sum_{j=1}^{V-V_q-V_k} \frac{1}{N_{NI} - n_q}. \tag{4.7}$$

   If the channel is full ($n_q = N_{NI}$), *vehicle i* may experience a (transmitter) collision with non-neighbour vehicles not in contention phase that can reserve one time-slot out of the whole selection range (NI). In this case equation 4.7 turns into

$$P_{collisionNotContendingOut} = \sum_{j=1}^{V-V_q-V_k} P(X_i = X_j)_{Full} = \sum_{j=1}^{V-V_q-V_k} \frac{1}{N_{NI}}. \tag{4.8}$$

2. A (transmitter) collision between *vehicle i* and out-of-range vehicles in contention phase does not only depend on choosing the same CW size, but also on the number of AIFS that are waited, if the vehicle stays in contention phase repeatedly. AIFS is a random number (*nAIFS*) and can be different for each vehicle. A collision takes place when the different vehicles have the same channel access delay ($AIFS + t$). As it is defined in [48], the probability that a *vehicle i* accesses the channel before all other contending vehicles is,

$$P(X_i < X_k) = \frac{1}{n_{CW\,i}} \sum_{i=1}^{n_{CW\,i}} \left[\prod_{k=2}^{K} P(X_k > AIFS_i + t)) \right]. \tag{4.9}$$

   This probability is calculated for each contending vehicle and the probability of collision is then given by,

$$P_{collisionContendingOut} = 1 - P(X_i < X_k). \tag{4.10}$$

On the other hand, if the channel is loaded ($V_q > 0$), *vehicle i* may experience (transmitter) collision with vehicles within its coverage range if they are in contention phase. If not, simultaneous transmissions are avoided by the carrier sensing. $P_{collisionIn}$ for *vehicle i* can be determined for the whole frame by summing over all the selection ranges, where $P_{collisionIn}$ probability is calculated the same as in equation 4.10 and equation 4.9

$$P_{collisionIn} = \frac{N_{NI}}{N_{NF}} \sum_{l=1}^{\frac{N_{NF}}{N_{NI}}} \left[P_{collisionContendingIn} \right]. \tag{4.11}$$

When using SoTDMA as MAC protocol, if the channel is loaded, *vehicle i* may experience (transmitter) collision with vehicles either out of its coverage range that can reserve one NTS out of its Selection Interval (SI). $P_{collisionOut}$ for *vehicle i* can be determined for the whole frame by summing over all the selection ranges,

$$P_{collisionOut} = \frac{N_{NI}}{N_{NF}} \sum_{l=1}^{\frac{N_{NF}}{N_{NI}}} \sum_{j=1}^{V-V_q-V_k} \left[P(X_i = X_j) \right] \tag{4.12}$$

Vehicle i may experience (transmitter) collision with vehicles within its coverage range that can reserve one NTS out of its SI. This happens when the counter (defining the number of successive frames that a certain NTS is used) of *vehicle i* and *vehicle j* expire at the same time. So it can be calculated

$$P_{collisionIn} = \frac{N_{NI}}{N_{NF}} \sum_{l=1}^{\frac{N_{NF}}{N_{NI}}} \sum_{j=1}^{V_q-1} \left[\frac{1}{n_N} P(X_i = X_j) \right] \tag{4.13}$$

The probability of selecting the same time-slot, $P(X_i = X_j)$, depends on the length of the overlap and if the SI is non-shifted or shifted with respect to the collider.

$$P(X_i = X_j)_{NonShifted} = \begin{cases} \frac{2n_m - n_{q''}}{n_{SI} - n_{q'}} & n_m \leq \frac{n_{SI}}{2} \\ \frac{n_m - n_{q''}}{n_{SI} - n_{q'}} & \frac{n_{SI}}{2} \leq n_m \leq n_{SI} \end{cases} \tag{4.14}$$

$$P(X_i = X_j)_{Shifted} = \frac{n_m - n_{q''}}{n_{SI} - n_{q'}} \quad n_m \leq n_{SI} \tag{4.15}$$

If the channel is full ($n_q = n_{SI}$), *vehicle i* may experience (transmitter) collision with another vehicle that can reserve one NTS out of the whole SI

$$P(X_i = X_j)_{NonShiftedAndFull} = \begin{cases} \frac{2n_m}{n_{SI}} & n_m \leq \frac{n_{SI}}{2} \\ \frac{n_m}{n_{SI}} & \frac{n_{SI}}{2} \leq n_m \leq n_{SI} \end{cases} \tag{4.16}$$

$$P(X_i = X_j)_{ShiftedAndFull} = \frac{n_m}{n_{SI}} \quad n_m \leq n_{SI} \tag{4.17}$$

5

MAC Performance in Vehicular Scenarios

5.1 SoTDMA Performance using Measured SNR time-series: tunnel scenario [1]

Until 2010 the work in [29, 49, 50] had shown that SoTDMA could be a suitable alternative to the IEEE802.11p MAC scheme for scheduling e-safety data traffic. This algorithm is inherited from the AIS automatic tracking system [51], used in the ship industry for identifying and locating vessels. Results showed that this MAC algorithm outperforms CSMA/CA when a deterministic physical layer abstraction is used. The question is: does SoTDMA still outperform in a rapidly time-variant and frequency-variant vehicle-to-vehicle (V2V) wireless channel? With this question in mind, the author carried out a SoTDMA performance analysis using SNR time-series retrieved from real vehicular scenarios.

The simulation scenario consists of one reference car driving in a tunnel, while at different time instants other vehicles enter its coverage area, overtake it and finally leave the coverage area.

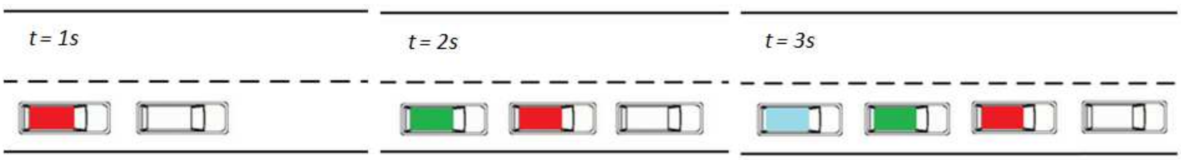

Figure 5.1: Tunnel scenario description t=1..3 s

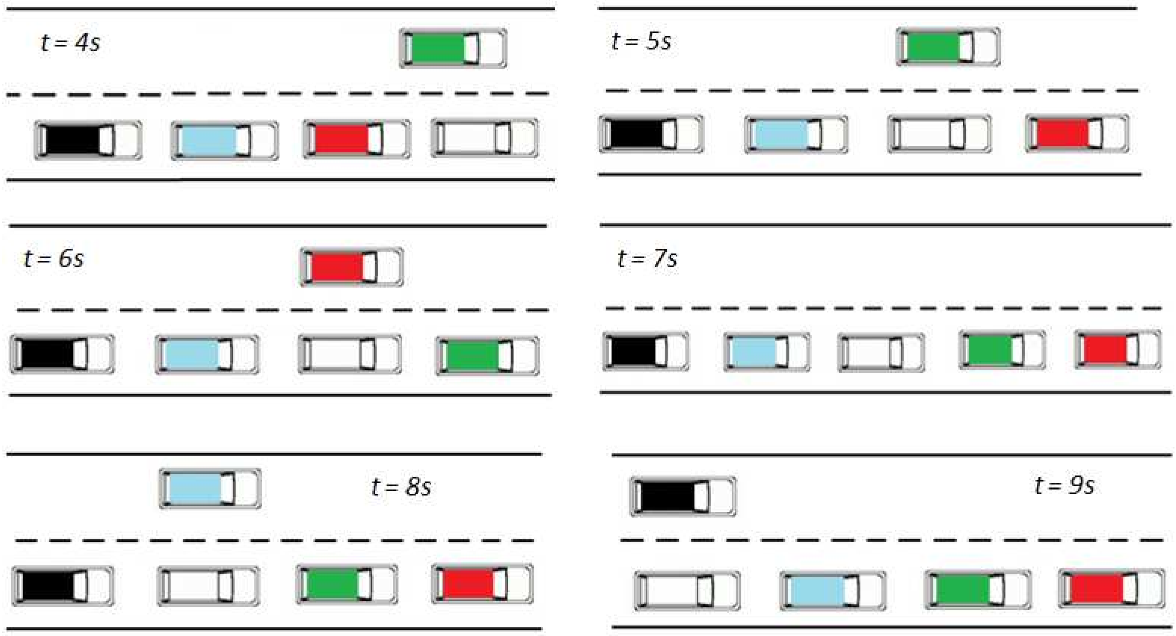

Figure 5.2: Tunnel scenario description t=4..9 s

The event-driven system model is implemented via Matlab's Simulink [52, 53] and Stateflow block sets. This choice of implementation is selected because it enables automatic translation into executable code on target hardware platforms. Blocks that specifically help SoTDMA modeling have been designed such as Network Traffic Generator, Vehicle Node and CAM Traffic Generator. The *Network Traffic Generator* contains mainly an event-based entity generator that reproduces messages of a configurable size and transmits them periodically. These messages are composed of configurable attributes (message size, communication delay, position). The *Vehicle Node* encompasses the *CAM Traffic Generator*, which after the first frame structure, begins generating messages at certain report rate. *Vehicle Node* also takes in a parameterized Stateflow block which actually implements the algorithm running inside each single node. The Stateflow chart is a library object [54] and each vehicle holds a MAC layer controller which takes in an instance of it. Therefore, every node of the framework is running an independent copy of the same algorithm.

Although many network simulation tools existed in 2010 (e.g. NS-2 [55], Qualnet [56] and OMNET++ [57]), the MAC layer performance is evaluated directly in Simulink to avoid the required interfacing between diverse tools. The following simple PHY layer abstraction is used for the throughput analysis. A data packet is considered as an indivisible unit as in [58].

The packet error probability is modeled by the frame error ratio (FER) at time t for the kth vehicle-to-vehicle link (0 s$\leq t \leq 9$ s and $k = 1, \ldots, 4$) which is idealized by

$$\mathrm{FER}_k(t) = \begin{cases} 0, & \text{if } \mathrm{SNR}_k(t) > \mathrm{SNR}_{\mathrm{threshold}}, \\ 1, \text{else.} & \end{cases} \tag{5.1}$$

A data packet is received successfully if the SNR is higher than the pre-defined threshold $\mathrm{SNR}_{\mathrm{threshold}}$ where it is assumed that collisions do not occur. SoTDMA is a collision-free protocol and the channel access is always provided. If all the slots are occupied, the vehicle willing to access the channel calculates which is its furthest away node, and waits until this furthest away node has sent all its frames (i.e. wait until its n indicator expires), and then begins transmitting in its time-slot. Based on [59], $\mathrm{SNR}_{\mathrm{threshold}}$ is set to 15 dB. Thus, the kth vehicle-to-vehicle link behavior is modeled by a time-series $\mathrm{SNR}_k(t)$ that was sampled during the ROADSAFE measurement campaign [60], which took place in September 2010. The V2V experiments were carried out in a two-lane tunnel scenario and each measurement run was $9 - 10$ s long.

The simulation parameters used are shown in Table 5.1. In a VANET where each superframe has got a transfer rate of 3 Mbps, each car transmits 500 byte long messages every 100 ms and there can cohabitate up to 75 vehicles within 1 s superframe.

Table 5.1: Parameter Setting for Simulation

	Parameter Settings
Transfer Rate, R	3 Mbps
Report Rate, H	10 Hz
Packet Size, N	500 byte
Superframe Period (SF)	1 s
Superframe Size	904 time-slots

Fig. 5.3 shows results for a more complex and realistic scenario based on the ROADSAFE measurement campaign data. It presents the time evolution of the channel state as four cars enter the network at different time instants. Each vehicle enters the initialization state (Vehicle1 at 0 s, Vehicle2 at 1 s,Vehicle3 at 2 s and Vehicle4 at 3 s). Channel state in Fig. 5.3 reassures that SoTDMA is collision-free, as expected.

The throughput analysis in this realistic context is now done from the point of view of a reference car that senses and processes the data traffic of channel. This car listens to the channel for the whole frame, the so called superframe, then waits until its life expires and listens to the channel again, so it will sense the channel periodically. This period will be defined by the superframe life, which in this case is 2, so the throughput will be analyzed at 2 s, 4 s, 6 s and 8 s.

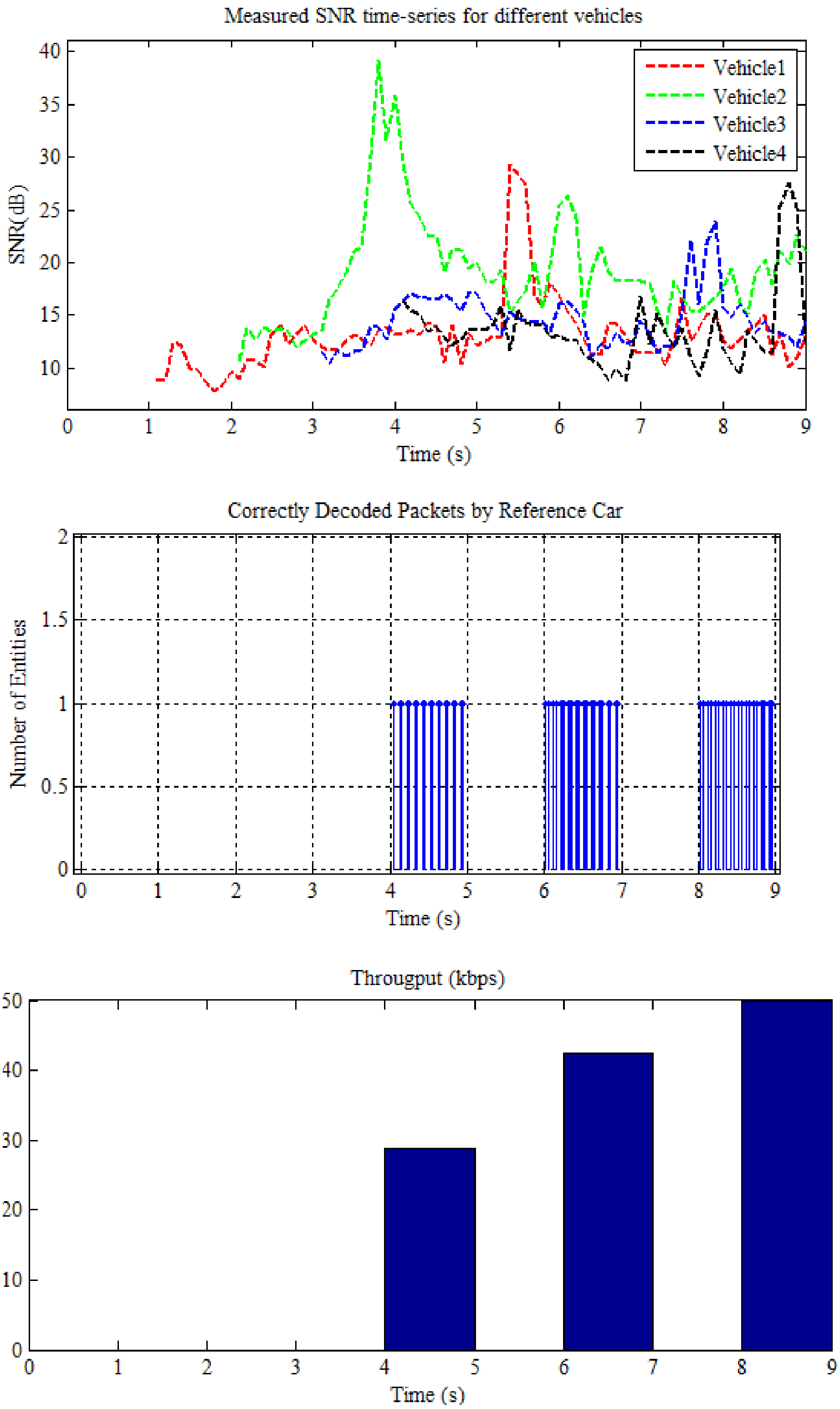

Figure 5.3: Channel structure, Measured SNR time-series for different vehicles, Correctly Decoded Packets and Throughput for a car driving along in the scenario

For high mobility scenarios, where the cars are driving fast and the propagation environment changes rapidly, a short superframe life would be more suitable, so the car can sense the changes on the road as fast as they are happening. Whereas for high traffic density scenarios, where the environment is constant and the variation slow, this parameter can be enlarged, as changes will not happen so quickly. After applying the aforementioned physical layer, Fig. 5.3 shows that at 2 s the SNR level of the sensed packets transmitted by Vehicle1 and Vehicle2 is lower than the SNR threshold defined by the reference car and that is why no correctly decoded packets or throughput is accounted at this point. But from 4 s to 5 s there are some correctly decoded packets and throughput increases to 28.93 kbps. Then it will be zero until it listens to the channel again and processes the new traffic. In this specific scenario the throughput obtained within 4 s and 5 s is generated from two vehicles transmitting, the throughput obtained within 6 s and 7 s is generated from three vehicles transmitting and the last one within 8 s and 9 s from all the vehicles transmitting.

The current IEEE802.11p MAC method is based on a probabilistic approach and does not guarantee upper bounds on the message delay. Future safety-related applications and infotainment services vastly differ in their requirements for message delay and link reliability. Therefore, a future enhanced IEEE802.11p MAC layer needs to satisfy these vastly differing requirements while coexisting with legacy MAC methods. Due to the collision-free operation and its structured channel access, SoTDMA is a suitable alternative for scheduling periodic broadcasted traffic. The work in [61] supports this, by concluding that SoTDMA outperforms CSMA/CA (the channel access algorithm of the IEEE802.11p MAC) in terms of delay and interference. From this point on in this thesis, further MAC performance analysis will also focus on message delay and link reliability.

5.2 Performance of a vehicular ad-hoc Network (VANET) during Start-Up phase: parking lot scenario [2]

The vehicular scenarios that have been studied so far in order to evaluate the performance of SoTDMA were highway scenarios, where a few new nodes turned up every frame. The entrance of new nodes was smooth and the nodes easily adapted to the current slot allocations. The work [29] was conducted for a saturated network and the results show that SoTDMA outperforms CSMA/CA in terms of packet dropping at the transmitter (none in the SoTDMA case) and successful channel access in comparison to CSMA/CA nodes.

The contribution [50] was conducted comparing SoTDMA with CSMA/CA of IEEE802.11p for a network that is not saturated. In such networks it was proven that SoTDMA outperforms CSMA/CA also when considering performance metric such as the distance between concurrently transmitting nodes.

It is already shown that SoTDMA behaves properly when a couple of new nodes are turned on every second. If there are already nodes in the system, which have a certain amount of allocated slots in the SoTDMA frame, the action of joining the SoTDMA frame is smooth and not very controversial, since the nodes must listen to the frame once before starting to allocate slots. However, what happens if many nodes within radio range are turned on during one frame duration? And also what happens if many nodes are turned on during consecutive frames?

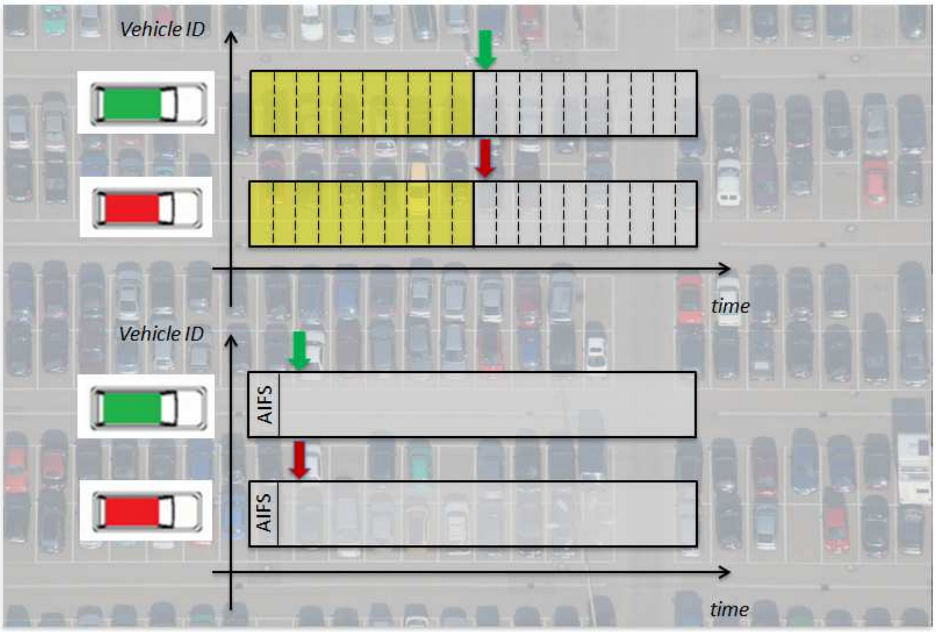

Figure 5.4: Several vehicles turned on during one frame duration might attempt to gain channel access at the same time due to the same perception of the frame (unintended slot reuse)

This can occur at a parking lot located outside a stadium, where, after a major event, many people will pick up their cars and start them approximately at the same time. When SoTDMA is used as channel access protocol (i.e. slotted-based), the upper graph shown in Fig. 5.4 displays the medium access situation during the start-up phase of two neighbour vehicles. During the first frame, the channel is sensed and then both nodes might attempt to gain channel access simultaneously due to the same frame perception. For the carrier sensing-based approach (see the lower graph in Fig. 5.4) this can also happen after the simultaneous sensing of the idle channel state during AIFS amount of time.

In such a scenario there are two use cases to be analyzed: when the newborn VANET is *(i) saturated* and *(ii) not saturated*.

i. *Saturated*: In this scenario there are more vehicles requesting resources than available time-slots. All nodes will allocate time-slots regardless of the number of nodes within radio range. When their SIs are fully booked with other nodes they will transmit at the same time as someone else at the parking lot (intended slot reuse). This scenario will probably create strong interference amongst the overlapping radio ranges of a great number of nodes, resulting in poor packet reception probability.

ii. *Not saturated*: In this scenario there are less requested resources than available slots. For this use case it is interesting to see how long it takes before all nodes have found their NTS, because nodes will allocate the same slot due to the same perception of the frame in the beginning (unintended slot reuse). It is interesting to determine how many frames it takes before SoTDMA has organized itself and no unintended slot reuse is present for different data traffic loads.

CSMA/CA as MAC method typically has less trouble with (*ii*) because when there are fewer nodes than resources available, the majority of all nodes will gain channel access as long as the attempts do not all come at the same time (choosing the same back-off value). However in (*i*) when the network load increases nodes will drop packets at the sender before they are even transmitted (blocked).

In order to test such a scenario, the following parameters have to be set-up:

a. Number or vehicles in the parking lot

b. Rate with which they appear (e.g., all nodes come during the same frame preferably Poisson distributed)

c. CAM/BSM rate and packet size

The scenario presented for evaluating CSMA/CA and SoTDMA methods is implemented using Matlab language. The data traffic generated by each vehicle is periodic and has a hard-deadline to meet. Each vehicle's initial transmission time is independent and random. In order to study the worst case, the scenario is static so the time persistency of the effects of the start-up phase can be analyzed in both, lightly-loaded scenario (50 vehicles) and heavily-loaded scenarios (up to 400 vehicles).

All the vehicles broadcast messages with a fixed data rate of 6 Mbps. The data traffic model is defined following the ETSI recommendations [62] for safety-related messages (broadcasted messages are 800 bytes long and are generated every 500 ms). The bandwidth requirements for each node is 12, 8 kbps.

The used physical model, is a channel model suitable for such highway scenarios. The Nakagami m model [63] has previously been identified as a suitable probabilistic channel model for the VANET setting ([64]). The small-scale fading and large-scale fading are both represented by the Nakagami m model. The probability density function (PDF) for the Nakagami m distribution is:

$$f(x; m, P_r(d)) = \frac{2m^m x^{2m-1}}{[P_r(d)]^m \Gamma(m))} e^{\frac{-mx^2}{P_r(d)}}, \tag{5.2}$$

where m represents the fading intensity, $P_r(d)$ the average received power at a distance d, and $\Gamma(m)$ is the gamma function. Rayleigh fading conditions, i.e., no line-of-sight exists, can be obtained through Nakagami by setting m to one. Higher values of m can be used for approximating Rician distributed channel conditions where a line-of-sight path exists, while for $m< 1$, the channel conditions are worse than Rayleigh distribution. The values of m are distance-dependent and presented in Tab. 5.2.

Table 5.2: The different m values in the Nakagami model [64]

Distance bin in meters	m
0-6	4.07
7-14	2.44
15-36	3.08
37-91	1.52
92-231	0.74
232-588	0.84

The averaged received power $P_r(d)$ is following dual-slope model:

$$P_{r,dB} \begin{cases} P_{r,dB}(d_0) - 10\gamma_1 log_{10}\frac{d}{d_0} \text{ if } d_0 \leq d \leq d_c \\ P_{r,dB}(d_0) - 10\gamma_2 log_{10}\frac{d}{d_c} - 10\gamma_1 log_{10}\frac{d_c}{d_0} \text{ if } d > d_c \end{cases} \tag{5.3}$$

where numerical values are presented in Tab. 5.3.

Table 5.3: The path gain model's parameters [65]

Parameter	Value
Path gain γ_1	1.8
Path gain γ_2	3.8
Cut off distance d_c [m]	80
Reference distance d_0 [m]	10
Wave length λ [m]	0.0508

The $P_{r,dB}(d_0)$ is calculated using the following free space path gain formula:

$$P_{r,dB}(d_0) = P_{t,dB} - 10log(\frac{\lambda^2}{(4\Pi)^2)d_0^2}), \tag{5.4}$$

where $d_0 = 10$ m and the wavelength, λ, is based on a carrier frequency of $f =$ 5.9 GHz. All vehicles use the same output power, $P_{t,dB}$, of 20 dBm (100 mW) and the resulting signal-to-interference-plus-noise (SINR) ratio at the receiver is calculated using the following formula [66]:

$$SINR = \frac{P_r}{P_n + \sum_{k=0}^{K} P_{i,k}}, \tag{5.5}$$

where P_r is the power of the desired signal, $P_{i,k}$ is the power of the k-th interferer, and P_n the noise power. The noise power is set to -99 dBm and the SINR threshold is set to 6 dB.

Table 5.4: Parameter Settings for CSMA/CA MAC Simulations

	Parameter Settings
AIFS (μs)	58
CW size	[0...3]
CCA Threshold (dB)	- 96

Regarding the parameter setting for CSMA/CA and SoTDMA MAC algorithms are shown in Tab. 5.4 and Tab. 5.5 respectively.

Table 5.5: Parameter Settings for SoTDMA Simulations

	Parameter Settings
Superframe Size (s)	1
Number of slots	904

Two kinds of start-up scenarios are simulated: *lightly-loaded and heavily-loaded scenarios*. Start-up scenarios are those in which a group of vehicles attempts to access an stable channel simultaneously. The vehicle inter-arrival time defines the frequency in which vehicles are activated in the scenario. It describes the inter-arrival time amongst vehicles already active and newly activated vehicles, and it is a tunable parameter. For these scenarios it is set to 0 s, as the effect to be studied is the impact of the amount of vehicles joining the channel within the same frame.

In the case of *lightly-loaded scenarios*, a urban road is simulated along which 25 or 50 vehicles in parking position are activated, and begin to transmit CAMs periodically. In Fig. 5.5 the MAC-to-MAC delay for all correctly decoded packets within 60 s simulation is shown, for CSMA/CA and SoTDMA respectively. In blue the packets that have arrived on-time, e.g. they have met 100 ms deadline, and in red the amount of packets that have arrived later than 100 ms. Analyzing the reception trend, it is very constant throughout the whole simulation time. Fig. 5.5 shows the performance for the first 6 s, that holds for the whole simulation time. In such lightly-loaded scenarios, as it is highly probable to sense the channel idle to transmit, CSMA/CA results show that all correctly decoded packets meet 100 ms.

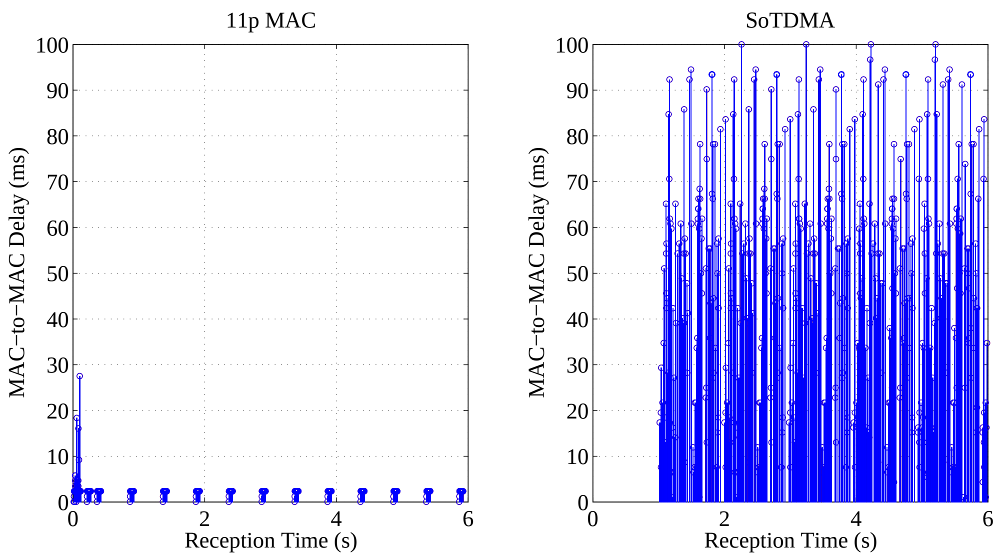

Figure 5.5: MAC-to-MAC delay of all correctly decoded packets vs. reception time for lightly-loaded scenarios (50 vehicles)

On the left-hand side of Fig. 5.5, the performance of CSMA/CA is depicted. During the first seconds, higher MAC-to-MAC delays are obtained due to the simultaneous medium access attempts, but then the back-off procedure leads to the distributed channel access across the medium. On the right-hand side the performance of SoTDMA depicts higher MAC-to-MAC delays but still all of them below 100 ms.

During the first second there are no correctly decoded packets as all the vehicles are in the initialization phase, i.e. listening the channel activity.

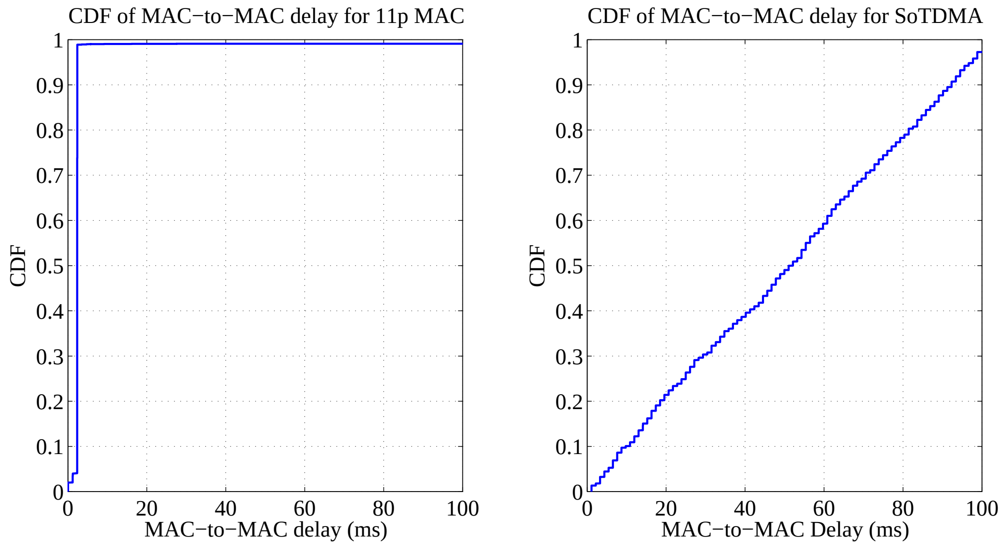

Figure 5.6: Empirical CDF of MAC-to-MAC delay of all correctly decoded packets for 100 ms deadline in lightly-loaded scenarios (50 vehicles)

In Fig. 5.6 the cumulative distribution function of the MAC-to-MAC delay is rendered for both MAC algorithms. The curves show the probability of generated messages to meet a deadline below the x axis, describing observable MAC-to-MAC delay values. A reliable performance is achieved when the CDF function reaches the 90%. For the 100 ms deadline both curves reach a reliable performance within 60 s simulation.

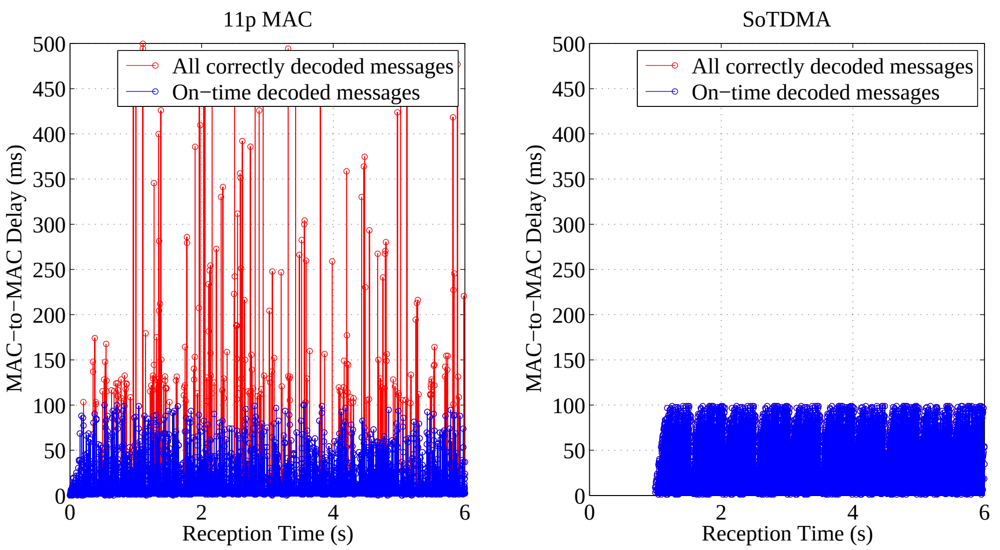

Figure 5.7: MAC-to-MAC delay of all correctly decoded packets vs. reception time for heavily-loaded scenarios (400 vehicles)

In the case of *heavily-loaded scenarios*, they reflect either a parking lot scenario, where more than 200 vehicles are activated, and begin to transmit CAMs/BSMs periodically; or a highway scenario where 300 to 400 vehicles are activated as an emergency occurs and begin to transmit DENMs periodically. In these kind of scenarios, CSMA/CA is less likely to sense the channel idle to transmit, so vehicles are backing-off within the first seconds until they transmit. Fig. 5.7 shows this trend where higher MAC-to-MAC delays are recorded throughout the simulation. In comparison to Fig. 5.5, only the ordinate limits have been changed for sake of clarity, from 0..100 ms to 0..500 ms. The MAC-to-MAC delay vs. reception time of SoTDMA, depicted on the right-handside of Fig. 5.8, looks similar to the results from Fig. 5.6, proving its stable and reliable performance. In Fig. 5.8 the results for CSMA/CA reflect that the performance has dropped in comparison to Fig. 5.6, as the vehicular traffic load has increased. The author defines as reliable performance applicable to e-safety data, as when the $CDF(\Delta t)$ raises up to 90% or above. Therefore Fig. 5.8 displays that neither CSMA/CA nor SoTDMA reach a reliable performance in heavily-loaded scenarios (up-to 400 vehicles). Still SoTDMA outperforms CSMA/CA by means of $CDF(\Delta t)$ level.

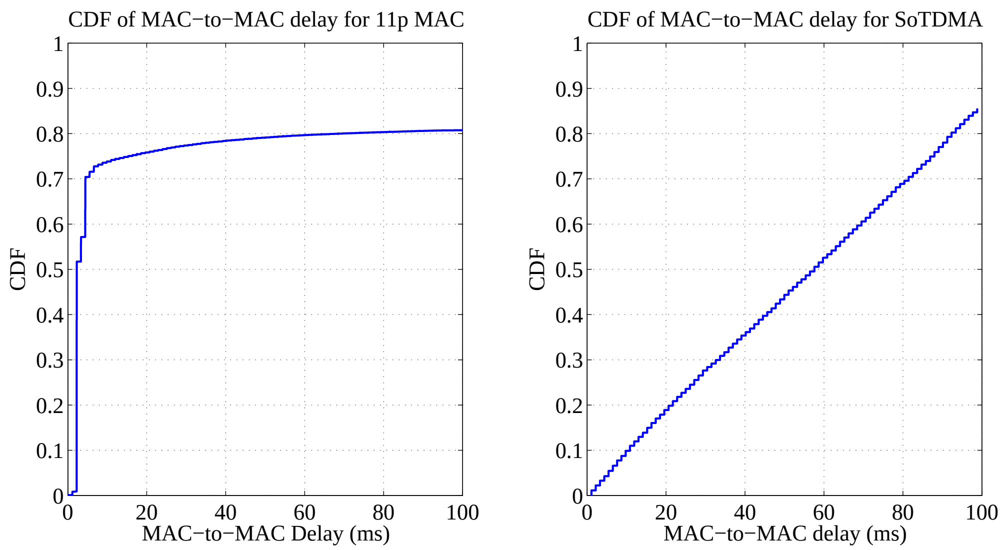

Figure 5.8: Empirical cumulative distributed function of MAC-to-MAC delay of all correctly decoded packets for 100 ms deadline in heavily-loaded scenarios (400 vehicles)

It is only when switching on the QoS feature of IEEE802.11p MAC, namely EDCA, where the traffic priorities are variable (see Tab. 5.6), that the $CDF(\Delta t)$ levels are enhanced. Using lower traffic priorities, the access attempts are more evenly distributed throughout the channel, and the curves are pumped up.

Using SoTDMA as benchmarking reference, IEEE802.11p MAC performance is enhanced to its level by setting the traffic priority of CAMs/BSMs to either medium or lowest priority, as shown in Fig. 5.9.

Table 5.6: MAC Parameter Settings for IEEE802.11p MAC Simulations

	Highest Priority Settings
AIFS (μs)	58
CW size	[0...3]
	Medium Priority Settings
AIFS (μs)	58
CW size	[0...7]
	Lowest Priority Settings
AIFS (μs)	71
CW size	[0...15]

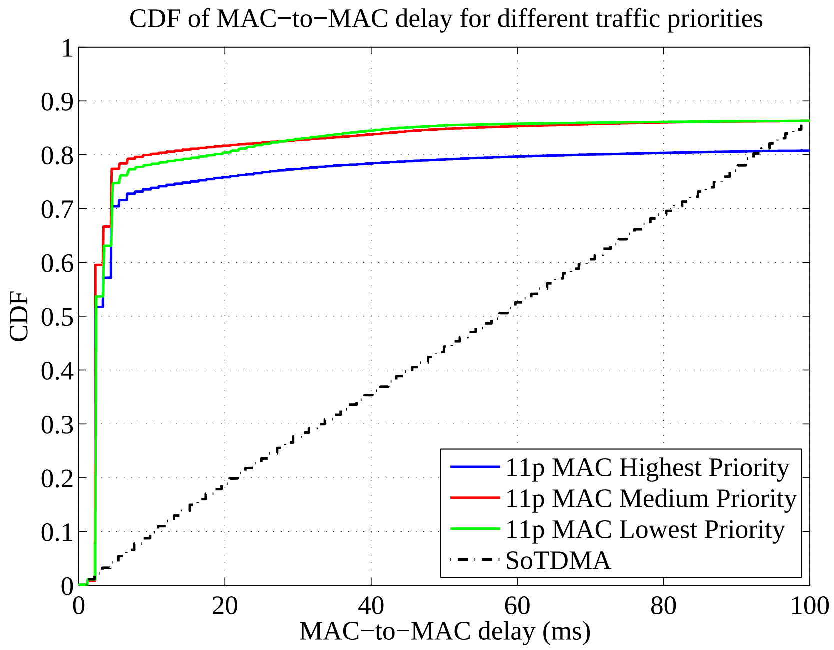

Figure 5.9: Empirical CDF of MAC-to-MAC delay of all correctly decoded packets for 100 ms deadline in heavily-loaded scenarios (400 vehicles) for different priorities

Tab. 5.7 validates, in terms of analytical results, the results depicted in Fig. 5.9, showing similar results for the same start-up scenario, using the collision probability performance indicators described in Section 4.7.

Anyhow, the aforementioned results demonstrate that in such heavily-loaded vehicular scenarios, reliability threshold of %90 cannot be achieved, using fixed transmit power or packet interval.

Table 5.7: Analytical Evaluation Results for Start-Up Phase of a VANET (400 vehicles)

MAC Scheme and Data Traffic	Probability of Collision (α)	$1-\alpha$
11p MAC Highest Priority	0.1955	0.8045
11p MAC Medium Priority	0.1470	0.853
11p MAC Lowest Priority	0.1416	0.8584
SoTDMA	0.1429	0.8571

5.3 Performance of the Three-State DCC mechanism: highway scenario with Transmit Power Control (TPC)

ETSI has proposed a DCC scheme in order to mitigate the IEEE802.11p MAC layer congestion issues at high vehicle densities. Previous work of the author in [2], showed that when using CSMA/CA (highest priority parameters) during the start-up phase of a VANET with high traffic density, the performance in terms of CDF of MAC-to-MAC delay falls towards 80% for 100 ms deadline, whereas SoTDMA results show a value of 85%. By changing to EDCA and setting the traffic priority characteristics to medium or lowest priority, SoTDMA benchmark is achieved. For CAM/BSM traffic it is more realistic to go for medium priority. DENMs are the ones to be used with highest priorities. Still in such crowded vehicular scenarios, where the VANET is in transient state, reliability threshold of 90% CDF of MAC-to-MAC delay is not feasable.

Some questions arise related to the performance of the aforementioned mechanism for reaching a reliable performance for VANETs: Does the DCC mechanism treat both priority traffic (CAM/BSM and DENM) the same way? A three-state DCC mechanism based on absolute maximum ratings has been proposed: Do vehicles in different states have similar performance? Is this three-state machine good enough to provide a reliable service? And how does the DCC mechanism adapt to a variable traffic density scenario? Does it provide dependability? i.e. not only to reach a reliable performance but to maintain throughout the simulation time, regardless of the traffic changes.

The simulated scenario is the one depicted in Fig. 5.10. In cases such as multi-level highway entries to big cities or multiple lane highways during rush hours, merging between internally well-organized VANETs driving in different directions take place.

On one hand, every node in an SoTDMA system has its own perception of the frame allocation and everyone has its own frame start (there are as many different frame start options as slots in the frame). Hence, nodes are slot synchronized but not frame synchronized. Nodes that are in the same geographical area will perceive approximately the same slot allocations in their respective frames.

Figure 5.10: As soon as the two clusters begin to merge it might happen that vehicles from Cluster A transmit at the same time as other cars from Cluster B. In this scenario packet collisions will occur.

On the other hand, in the case of the IEEE802.11p MAC scheme every node can sense other neighbours transmiting a signal above its carrier sensing threshold level. In both cases, the nodes will be organized and unintended slot reuse (i.e. unintended collision) is unlikely to happen in unsaturated situations. But what happens if a cluster, called A, traveling in one direction meets another cluster, called B, merging onto the same road? Cluster A is well-organized internally, i.e., all nodes have found transmission slots without interfering with each other and then cluster B suddenly turns up, also well-organized internally. How long will it take before cluster A and cluster B have re-organized and created a new "common" perception of the frame and concurrent transmissions (using the same time-slot as a node located close by) are diminishing?

The study of the hidden node terminal problem for CSMA/CA has been analyzed for switched Ethernet networks [67] as well as in VANETs [68]. Namely [68] studies the severity of the impact of the hidden node in the performance of both CSMA/CA and SoTDMA. Whereas SoTDMA performs close to the upper bound for receivers in the vicinity if the transmitter, CSMA/CA experiences partial overlapping transmissions from hidden node terminals due to the absence of synchronization. In the case of SoTDMA, as long as their reuse factor does not expire, they will keep on transmitting and packet collisions will occur. In the case of EDCA, collisions will occur as long as the messages transmitted by the colliding nodes are not updated.

The amount of collisions depends on:

- *The amount of vehicles in both clusters*: The higher the channel load of each cluster is, the less the channel availability is and hence, the higher the collision probability will be amongst vehicles belonging to different clusters.
- *Each vehicle's reuse factor when merging process begins*: Collisions keep happening as long as the reuse factors of colliding nominal transmission slots (NTSs) of SoTDMA nodes do not expire. The larger reuse factor is, the greater the number of collisions will be.
- *Each vehicle's contention window and the nAIFS when the collision happens*: Collision happens every time EDCA nodes have the same $CW + nAIFS$ value. The smaller CW amplitude is, the greater the number of collisions.

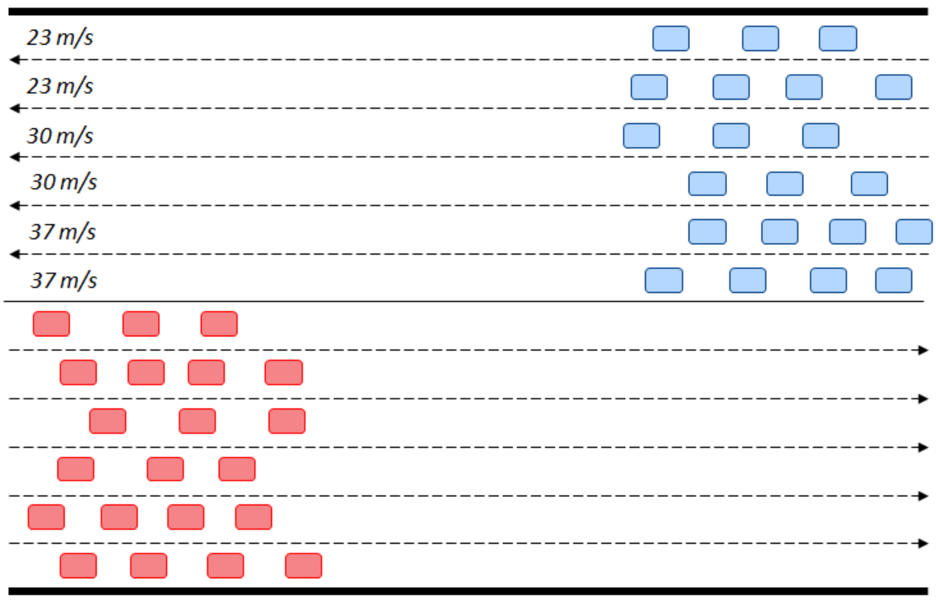

Figure 5.11: Scenario description of two VANETs merging use case.

The vehicles on the lead position of the cluster (the ones situated in front of the cluster), could inform the neighbours as they sense collisions, so the rest, in case of using SoTDMA, assign their reuse factors a lower value, such that they expire as soon as possible. When EDCA is the MAC protocol, CW amplitude could be reassigned so that the collision probability decreases.

To test such a scenario, the following parameters have to be set-up:

a. Number of vehicles in each cluster,

b. CAM/BSM rate and packet size and

c. Rate with which nodes appear in each cluster.

The scenario simulated is a six lane highway scenario where 400 vehicles (80% channel load) are traveling in opposite directions (see Fig. 5.11). Nodes appear Poisson distributed and start to send uniformly distributed CAM/BSM data. Vehicles enter the scenario at 0 m and 5000 m depending on the direction they are driving in. Regarding the movement simulation, there are three parameters to be set per new vehicle added to the VANET:

- *Initialization time*: It represents the simulation time in which the vehicle is added to the simulation environment. Depending on the *vehicle inter-arrival time* vehicles within the same lane are added more frequently. In these simulations worst case scenario is analyzed, setting *vehicle inter-arrival time* to 1 s, so vehicles are added to the same lane every second.
- *Lane*: It represents the driving lane in which the vehicle will move, it sets a fixed *y axis value*, and then vehicle move along the *x axis*.
- *Speed*: Depending on the *lane* the vehicle is driving, it will have an associated speed ([50]).

All the vehicles broadcast messages with a fixed data rate of 6 Mbps. The data traffic model is defined following the latest ETSI recommendations redefined in [65] for safety-related messages (broadcasted messages are 400 bytes long including all protocol overhead and are generated every 500 ms).

The used physical model, is similar to the one described in Section 5.2. Small scale and large scale fading are represented by the Nakagami m model, also for vehicular channel modeling. A more suitable set of m values is retrieved from the most updated Draft ETSI TR 102 861 V. These are shown in Tab. 5.8.

Table 5.8: The different m values in the Nakagami model [65]

Distance bin in meters	m
0-50	3
51-150	1.5
151-	1

The average received power, P_r, is assumed to follow the dual slope model suggested in [63]. Also the path gain model parameters (γ_2, d_c) have been tuned so that they fit the ETSI requirements of achieving a 1000 m coverage range at maximum transmit power when the CST is set to -85 dBm. The parameters are the same as in Table 5.3 (γ_1, γ_2, d_c, d_0, λ), and they are now set to (1.9, 3.6, 177, 10, 0.0508).

Cut-off distance d_c is calculated as in [69], from the first Fresnel Zone with first ground reflection,

$$d_c = d_b + \frac{\lambda}{4} = \frac{4h_T h_R - \frac{\lambda^2}{4}}{\lambda} + \frac{\lambda}{4}, \tag{5.6}$$

where d_b is the distance at which the first Fresnel zone touches the ground or the first ground reflection has traveled $d_b + \frac{\lambda}{4}$ to reach receiver; h_T is the transmitter height, h_R is the receiver height and λ is the wavelength for 5.9 GHz carrier frequency.

For the No DCC use case, the output power is set to $P_{t,dB}$, of 23 dBm and the signal-to-interference-plus-noise ratio at the receiver is calculated using the Eq. 5.5 from Section. 5.2. The noise power is set to -99 dBm and the SINR threshold is set to 6 dB, a value typical for the 6 MBit/s modulation scheme.

Regarding the parameter setting for the IEEE802.11p MAC algorithm, Tab. 5.6 in Section 5.2 shows the AIFS and the back-off value, which is randomly selected depending on the priority. Clear channel assessment (CCA) threshold is set to -96 dB.

The performance in such scenarios is studied in time (see Fig. 5.12), to analyze the evolution of the performance indicators before, during and after merging. These analysis can be classified as individual node performance and system performance.

Fig. 5.13 shows simulation results of an individual node during the merging of two VANETs. In the top figure the dynamic evolution of the simulated scenario is depicted.

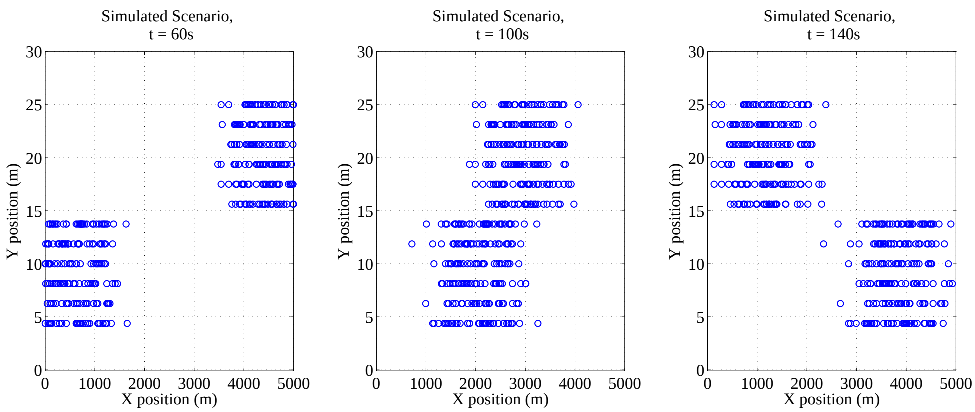

Figure 5.12: Scenario description of two VANETs merging use case: Simulator Output

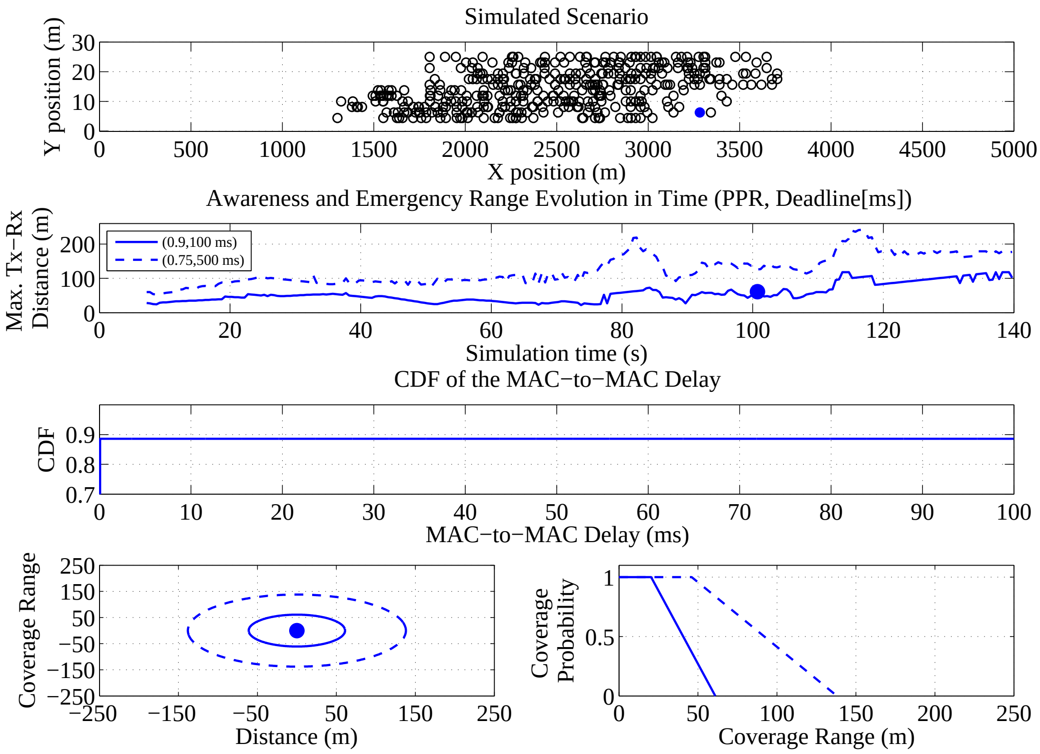

Figure 5.13: Simulation Results for a Vehicle in Relaxed State

The scenario displayed is the merging situation at t=100 s. The performance indicators studied are:

- *Awareness and Emergency Coverage Range vs Time*: It shows the maximum transmitter-receiver distance vs time for two different QoS defined by probability of packet reception and deadline (PPR, Deadline (ms)). Dotted line shows the results for more permissive QoS (0.75,500 ms) and solid line results for more restrictive QoS (0.9,100 ms). For safety-related data traffic more restrictive parameter settings is selected. In the work of [47] it is stated that for safety-related applications a PPR value of 85% is not enough. The dot represents the situation in time of the individual node (node under study), when the rest of the performance indicators are evaluated.

- *Cumulative Distribution Function of the MAC-to-MAC Delay vs MAC-to-MAC Delay*: Sticking to the aforementioned QoS restriction, the significative CDF level to be analyzed is the related to 100 ms deadline.

- *Coverage Probability vs Coverage Range*: In the case of using 500 ms packet interval, two packets are sent per frame, therefore *coverage probability* has two levels. For variable packet interval *coverage probability* is multilevel.

- *Coverage Range Evolution*: Is a dissemination reliability indicator. It defines the furthest away distance reached by a broadcast per channel realization (frame). The dot represents the individual node (node under study).

Simulation results using the plain EDCA (No DCC implemented) are depicted in Fig. 5.13. In this case all the vehicles have the same parameter setting so their performance differs just due to the impact of the vehicular scenario and not because of having disparate PHY or MAC parameter settings. For the system performance, the CDF of the MAC-to-MAC delay of all the messages exchanged in time and the evolution of the reliability indicator in time are analyzed.

The next step is the implementation of a suitable DCC mechanism, which enhances the plain EDCA performance also under strong traffic density variations. ETSI presented in [12] a three-state solution, where the crosslayer approach sets the PHY layer parameters packet interval (PI), modulation and coding schemes (MCS), transmit power (P) and carrier sensing threshold (CST) depending on the MAC layer parameter channel load (CL). In this work a simplified version of this three-state state machine is implemented. The values used in Fig. 5.14 are the limits given as absolute maximum allowed parameter range and not the values intended to be used as state parameters.

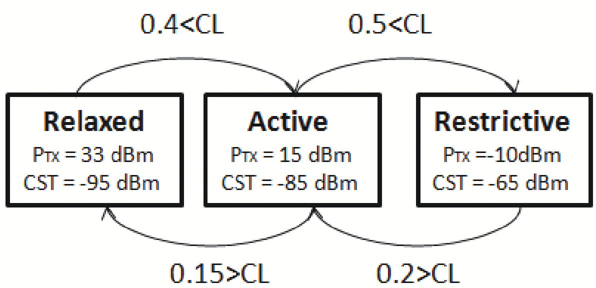

Figure 5.14: Three-State Maximum Values DCC Mechanism design

The aforementioned state machine consists of a relaxed, active and restrictive state with associated transmit parameters and state transition rules. When channel load is too high, the DCC algorithm tends to change all parameters simultaneously to ease congestion. A state transition to a higher congestion state occurs when all measured CLs for the past second are larger than CL_{UP}(0.4,0.5). The transition towards lower congestion state occurs if the CLs measured during the past five seconds are lower than CL_{DOWN}(0.15,0.2). CAMs/BSMs and DENMs have got a fixed PI and MCS, so just P and CST parameters are changed from state to state.

An alternative three-state DCC solution is proposed by the author (see Fig. 5.15) in order to enhance the performance of the maximum values DCC mechanism.

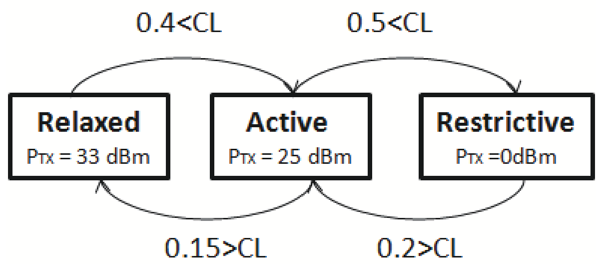

Figure 5.15: Three-State Our DCC Mechanism design for CST=−90 dBm

5.3.1 Individual Node Performance

In order to evaluate the impact of the priority of the data traffic, the emergency range evolution (for a QoS (0.9,100 ms)) in time is analyzed for highest and medium priority traffic. When a DCC mechanism is introduced, different node behaviour has to be analyzed (vehicles initialized in different DCC states, that have different perceptions of the channel load), in order to evaluate if the DCC is stable and properly designed.

In the simulated merging scenario, during the first 60 s the individual VANETs driving in opposite directions are loaded, each with 200 vehicles. The peak in 80 s shows an increment of the channel load as the vehicles driving in opposite direction begin to enter reference vehicle's coverage range. From that moment on, the channel load gets heavily-loaded (up to 200 vehicles driving in opposite direction are going to enter the sensing range of the reference vehicle). This has an impact on the increment of the channel access delay, i.e. the more vehicles are sensed the more the reference vehicle backs off. Thus, the MAC-to-MAC delay of the message to be broadcasted increases. This has an effect of reduction on the coverage range, as the channel access is so high that only the vehicles in the vicinity of the transmitter get the safety message on-time. As both VANETs separate the channel load is eased, the emergency range achieves another peak and finally decreses as two VANETs fall apart from each other.

A vehicle initialized in *relaxed state*, i.e. a node that has joined an empty or very lightly-loaded VANET, is usually a platoon leader. It is the vehicle that senses the highest number of changes in the channel load and because of that the emergency range is the most fluctuting. The No DCC curve has the narrowest coverage ranges. For highest priority data traffic depicted on the left-hand side of Fig. 5.16, both DCC mechanisms enhance the No DCC performance.

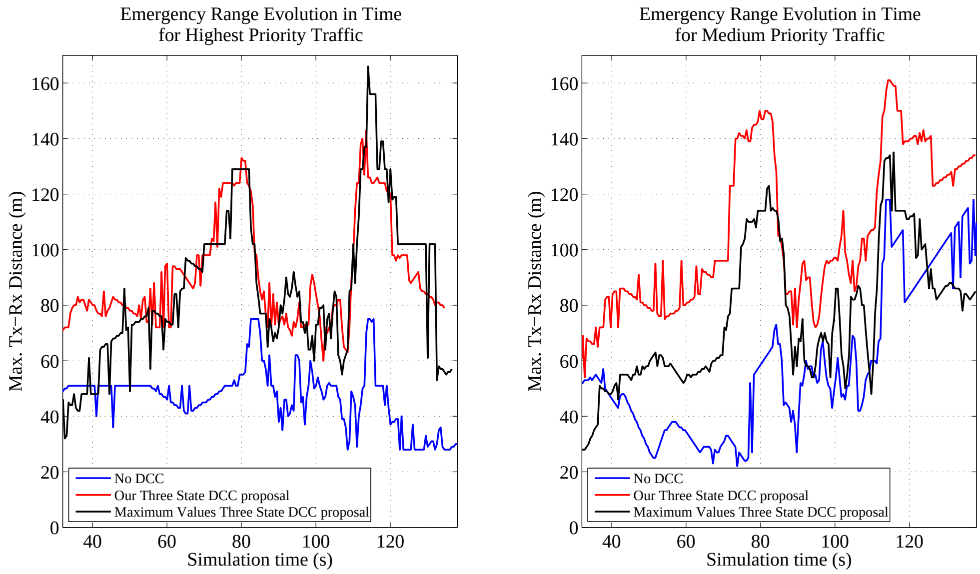

Figure 5.16: Emergency Range vs Simulation Time for a Vehicle initialized in *Relaxed State*

Both DCC curves follow a similar trend, which means that the same vehicle implementing either of them falls in similar states throughout the simulation time. The collision probability in both cases affects both curves similarly. Even in totally merged scenario (400 vehicles) coverage range is doubled (from 40 m to 80 m). On the right-hand side, for medium priority data traffic, the three-state DCC design proposed by the author outperforms the maximum value three-state DCC mechanism. The difference between the DCC curves relates to the collision probability affecting differently both curves.

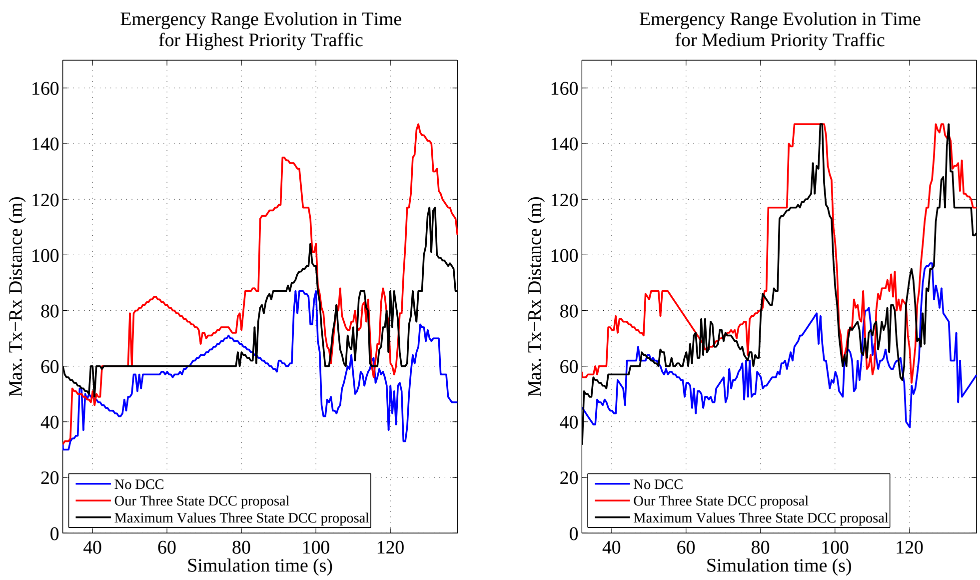

Figure 5.17: Emergency Range vs Simulation Time for a Vehicle initialized in *Active State*

A vehicle initialized in *active state* enters a previously-loaded VANET (100 vehicles). In Fig. 5.17 again both DCC mechanism outperform the No DCC results. In the case of using highest priority traffic profile No DCC and author's three-state DCC proposal show similar results to the Fig. 5.16. Whereas maximum value three-state DCC proposal depicts narrower coverage ranges. This is because the parameter setting is more restrictive. On the right-hand side, for medium priority, as the collision probability changes, the coverage ranges get wider within the same time domain than in Fig. 5.16 in the case of No DCC and author's three-state DCC proposal. This is not the case for the maximum value three-state DCC.

And lastly, a vehicle initialized in *restrictive state* accesses an already heavily-loaded channel. Fig. 5.18 depicts for highest priority, that only maximum values three-state DCC proposal outperforms No DCC. The maximum value three-state DCC uses a CST of −65 dBm for these vehicles. This shows that a CST of −90 dBm used in either No DCC or the author's three-state DCC design, might be a too sensitive for these vehicular scenarios. On the right-hand side, for medium priority data traffic No DCC and our three-state DCC proposal show similar results. Both outperforming maximum value three-state DCC.

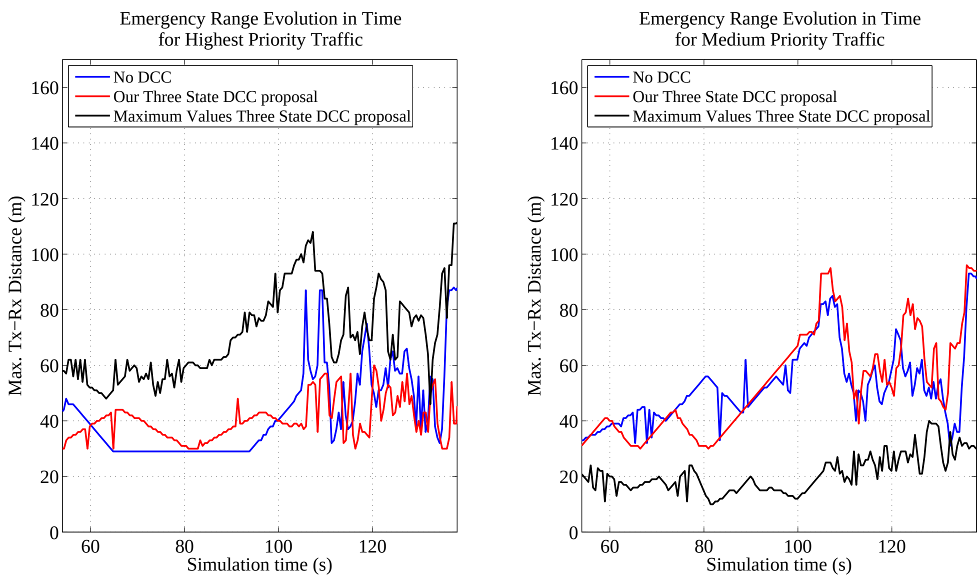

Figure 5.18: Emergency Range vs Simulation Time for a Vehicle initialized in *Restrictive State*

The aforementioned results reflect the performance in terms of coverage range. To this performance indicator, the author wants to corroborate the conclusion drawn in Section 5.2, namely that the medium priority data traffic is the most suitable traffic profile for CAMs/BSMs in such heavily-loaded traffic scenarios.

Therefore in further analysis only medium priority data traffic results are going to be presented. When analyzing the overall performance of the different DCC mechanisms, the most strongly varying curves from state to state are the ones related to the maximum value three-state DCC mechanism. This is due to the varying CST value from state to state. For sake of predictability, the author suggests to set a fix CST for scheduling e-safety traffic.

For safety-related data is not good enough just to take into account the coverage range (how far the transmission gets) but also the delay has to be analyzed. It is necessary to evaluate the dissemination of the information for a certain deadline. Is good to analyze both parameters as the two pieces of one puzzle. The next task to accomplish, is to carry out the (Δt,Δd) analysis in time (*before*, *during* and *after* merging) for the three nodes initialized in different states of the DCC mechanism.

Before merging

Fig. 5.19 shows the output of the simulation results at $t = 60$ s. The top subfigure depicts the simulation scenario where the outlined blue node is the evaluated vehicle initialized in *relaxed state*. Author's three-state DCC proposal outperforms the rest in terms of coverage range (Δd) but the maximum values three-state DCC proposal outperforms the rest in terms of MAC-to-MAC delay (Δt). Still both DCC mechanisms perform reliably (i.e. CDF of MAC-to-MAC delay level $\geq 90\%$)

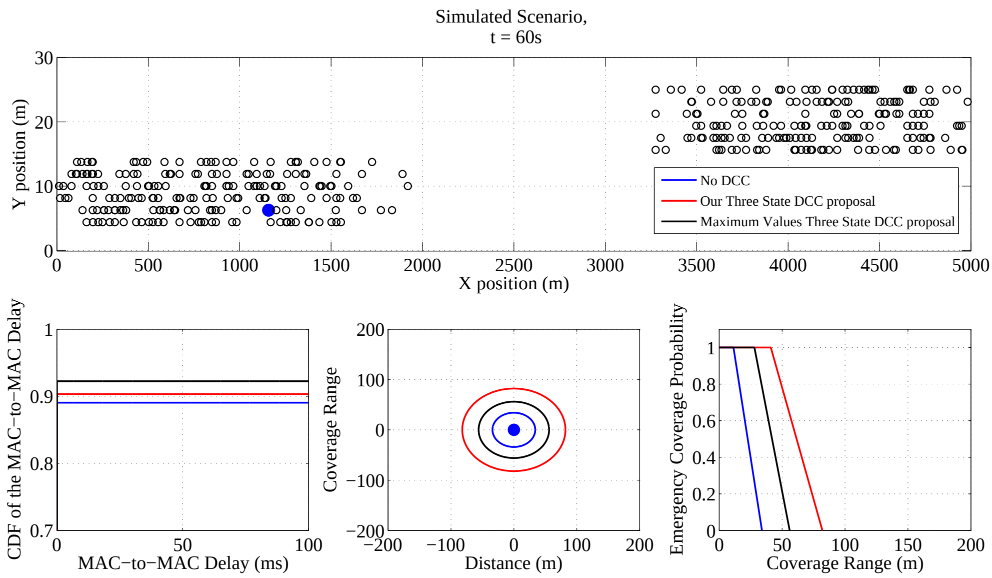

Figure 5.19: Simulation Results for a Vehicle initialized in *Relaxed State* (t=60 s)

Table 5.9: Simulation Results (CDF(Δt),Δd) for a Vehicle initialized in *Relaxed State* (t=60 s)

	(CDF(Δt),Δd)
No DCC	(0.89, 34 m)
Our Three-State DCC proposal	(0.9, 82 m)
Maximum Values Three-State DCC proposal	(0.92, 56 m)

For a vehicle initialized in *active state* results in Tab. 5.10 evidence that the author's three-state DCC proposal outperforms in terms of MAC-to-MAC delay and coverage range (Δt,Δd), both No DCC and the maximum values three-state DCC mechanism results. Again both DCC mechanisms reach reliable performance. Comparing the results to a vehicle initialized in *relaxed state* (see Tab. 5.9), the CDF(Δt) values are simular and Δd values have increased due to the higher number of vehicles in the vicinity of the reference vehicle.

Table 5.10: Simulation Results (CDF(Δt),Δd) for a Vehicle initialized in *Active State* (t=60 s)

	(CDF(Δt),Δd)
No DCC	(0.88, 55 m)
Our Three-State DCC proposal	(0.98, 77 m)
Maximum Values Three-State DCC proposal	(0.92, 65 m)

It is in the case of a vehicle initialized in *restrictive state*, Fig. 5.20, where the proposed three-state DCC mechanism draws a better performance in coverage range, Δd, at the cost of losing reliability, CDF(Δt).

Table 5.11: Simulation Results (CDF(Δt),Δd) for a Vehicle initialized in *Restrictive State* (t=60 s)

	(CDF(Δt),Δd)
No DCC	(0.88, 40 m)
Our Three-State DCC proposal	(0.85, 40 m)
Maximum Values Three-State DCC proposal	(0.92, 20 m)

Comparing the results to a vehicle initialized in *relaxed state*, Δd values are smaller due to more restrictive parameter setting. The maximum value three-state DCC is the most conservative selecting its parameter settings, and decreases the coverage to the half of the No DCC results in order to pump the CDF(Δt) level above the reliability threshold.

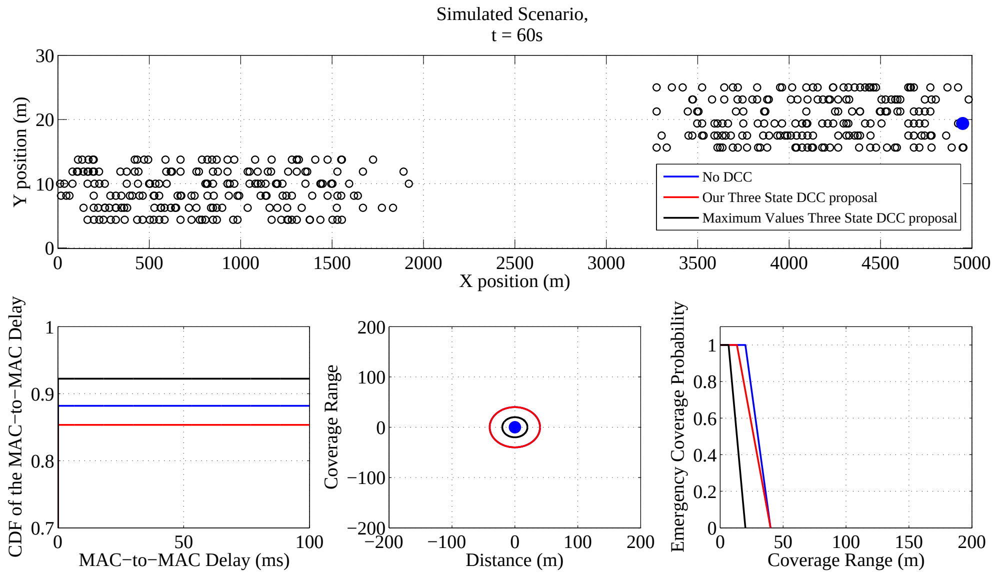

Figure 5.20: Simulation Results for a Vehicle initialized in *Restrictive State* ($t = 60s$)

Merging

During the merging scenario (common channel perception up to 400 vehicles), the adaptiveness of the DCC mechanism is put to the test, for a strongly varying channel load density. For a vehicle initialized in *relaxed state* No DCC coverage range is increased and reliability is reached using both DCC mechanisms. The three-state DCC proposal improves the coverage range of the maximum values three-state DCC mechanism in 10 m and of the No DCC in 36 m. Results are depicted in Fig. 5.21.

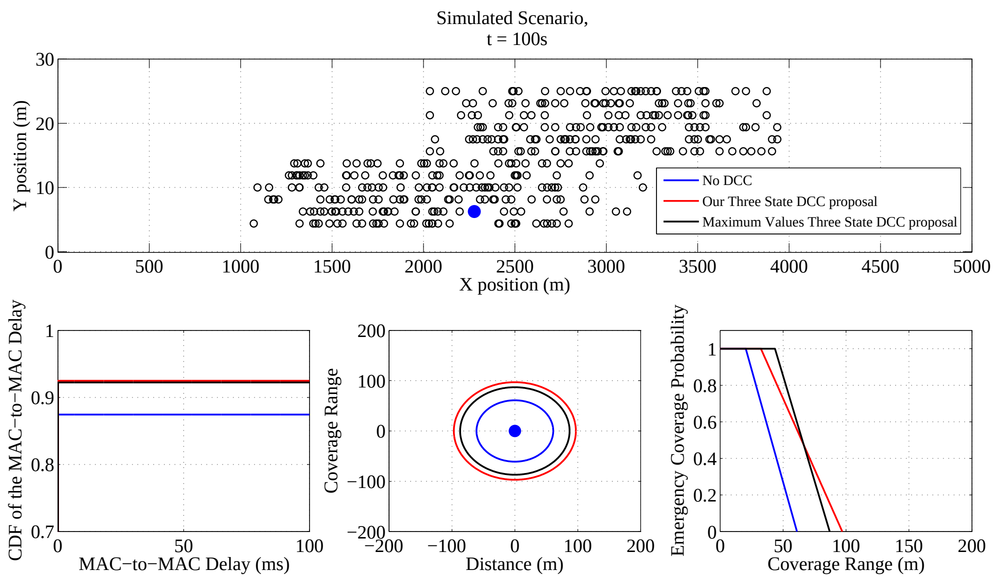

Figure 5.21: Simulation Results for a Vehicle initialized in *Relaxed State* (t=100 s)

Table 5.12: Simulation Results (CDF(Δt),Δd) for a Vehicle initialized in *Relaxed State*(t=100 s)

	(CDF(Δt),Δd)
No DCC	(0.87, 61 m)
Our Three-State DCC proposal	(0.92, 97 m)
Maximum Values Three-State DCC proposal	(0.92, 87 m)

In comparison to the results of a vehicle initialized in *relaxed state* before merging (see Tab. 5.9), CDF(Δt) values are simular and Δd values have increased due to the higher number of vehicles in the vicinity of the reference vehicle (traffic situation has evolved to a merged situation).

The results for a vehicle initialized in an *active state* node are equiparable to the ones shown in Tab. 5.12. This is because in this time instant both scenarios are similar for both nature nodes.

The problem arises once again with the performance of a vehicle initialized in *restrictive state*. Fig. 5.22 renders how a more conservative parameter setting selection (implemented in the maximum values three-state DCC) leads to a reliable performance. But it clearly points out that the DCC mechanism should be tuned properly, as 14 m coverage range is too narrow for disseminating e-safety information.

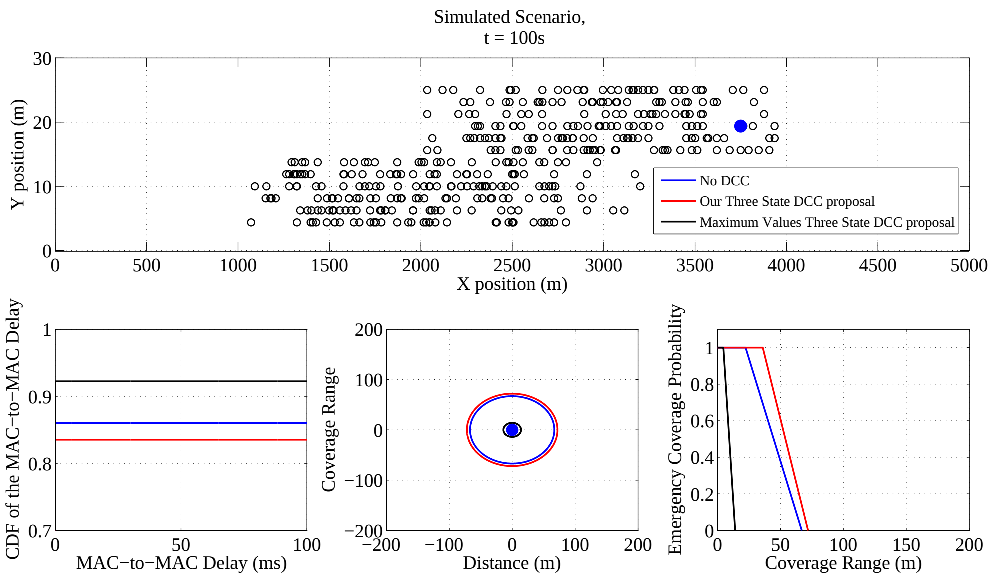

Figure 5.22: Simulation Results for a Vehicle initialized in *Restrictive State*(t=100 s)

Table 5.13: Simulation Results (CDF(Δt),Δd) for a Vehicle initialized in *Restrictive State*(t=100 s)

	(CDF(Δt),Δd)
No DCC	(0.86, 67 m)
Our Three-State DCC proposal	(0.83, 72 m)
Maximum Values Three-State DCC proposal	(0.92, 14 m)

After merging

Finally after merging, the coverage range values adapt to the new situation but the reliability trends hold to the fashion observed in t=60, 100 s. Both three-state DCC mechanisms show similar results in terms of reliability for a vehicle initialized in *relaxed state* and in *active state*, Tab. 5.14 and Tab. 5.15 respectively.

To sum up, different vehicles have shown different performances depending on the state they are in. As expected, DCC mechanisms enhance the plain IEEE802.11p MAC performance in terms of MAC-to-MAC delay and coverage range for vehicles initialized in *relaxed* and *active state.* The reliability trend holds throughout the simulation time, and the coverage ranges adapt to the varying vehicular traffic scenario (which follows the emergency coverage range trend presented in Fig. 5.16 and Fig. 5.17).

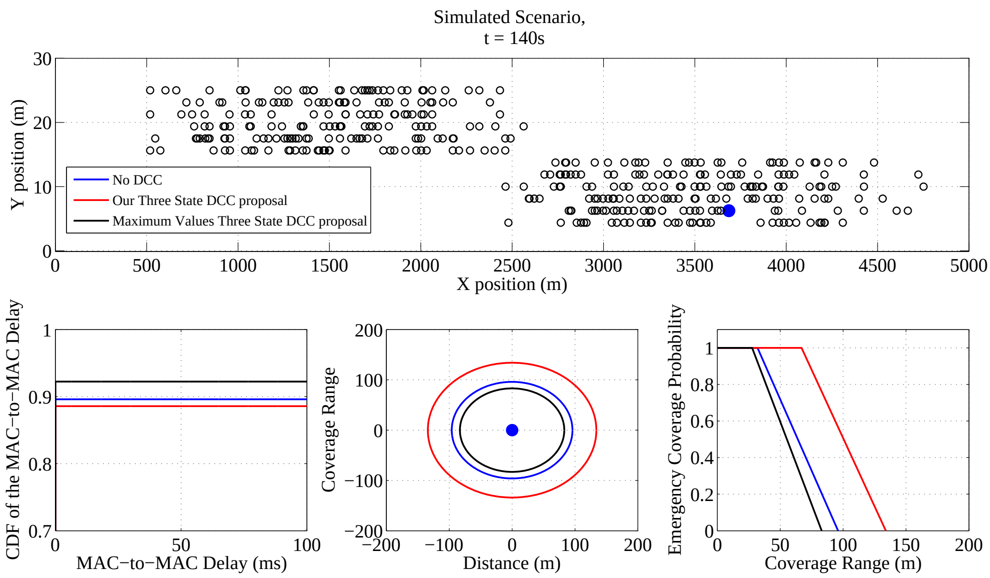

Figure 5.23: Simulation Results for a Vehicle in initialized in *Relaxed State*(t=140 s)

Comparing the results in Tab. 5.14 to the results in Tab. 5.15, performance shows that at t=140 s both nodes draw different results because they experience different CL, and hence fall in different states of the DCC mechanism. For a vehicle initialized in *relaxed state* only maximum values three-state DCC reaches a reliable performance at the cost of losing coverage range. Whereas for a vehicle initialized in *active state* both DCC mechanisms achieve a reliable performance and enhace also Δd.

Table 5.14: Simulation Results (CDF(Δt),Δd) for a Vehicle initialized in *Relaxed State*(t=140 s)

	(CDF(Δt),Δd)
No DCC	(0.89, 96 m)
Our Three-State DCC proposal	(0.88, 140 m)
Maximum Values Three-State DCC proposal	(0.92, 83 m)

Table 5.15: Simulation Results (CDF(Δt),Δd) for a Vehicle initialized in *Active State* (t=140 s)

	(CDF(Δt),Δd)
No DCC	(0.89, 54 m)
Our Three-State DCC proposal	(0.98, 121 m)
Maximum Values Three-State DCC proposal	(0.92, 118 m)

Table 5.16: Simulation Results (CDF(Δt),Δd) for a Vehicle initialized in *Restrictive State* (t=140 s)

	(CDF(Δt),Δd)
No DCC	(0.83, 94 m)
Our Three-State DCC proposal	(0.83, 96 m)
Maximum Values Three-State DCC proposal	(0.92, 31 m)

Lastly, the recurrent problem for a vehicle initialized in *restrictive state* (represented in Tab. 5.11, Tab. 5.13, Tab. 5.16) reappears and generates the following question: Is the amount of vehicles initialized in *restrictive state* important enough to empoverish significantly the overall system performance? And this question leads to the next performance analysis, namely the VANET performance.

5.3.2 VANET Performance

The final analysis to make is the time evolution of the whole system performance. Fig. 5.24 shows the simulated scenario for t=140 s, then the CDF of the MAC-to-MAC delay of all received messages at that time instant and records the reliability indicator in time, setting it to $'1'$ if the CDF(Δt) is above 90% and to $'0'$ if it falls below the threshold.

Reliability indicator shows the dependability of the system. From the 46 s on the No DCC performance is unreliable and does not improve anymore due to collisions. With the DCC mechanisms, the system stays reliable for longer time but there is a transient effect, i.e. reliability gap, until it stabilized ($91 - 127$ s) for 400 vehicles. This gap relates to the performance indicator defined in Section 4.4, $t_{stab} = 36$ s. When separating the transient effect reappears.

In conclusion, the three-state DCC mechanism increases reliability for high vehicle densities but dependability is not reached for variable traffic densities. For that purpose either multistate designs or another physical layer parameter settings (e.g. transmit rate control) should be tried out.

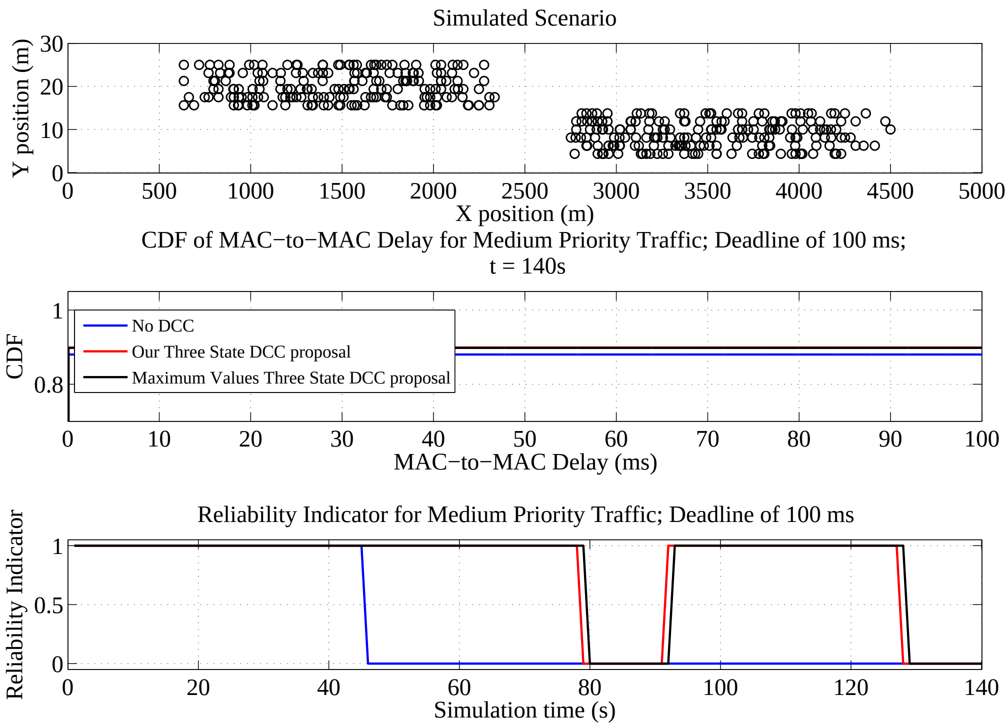

Figure 5.24: System Performance for two VANET merging scenario: CDF of MAC-to-MAC Delay and Reliability Indicator

5.4 Performance of the Multistate Active DCC mechanism: highway scenario with TPC and Transmit Rate Control (TRC) [3]

It is important in VANETs where safety data is present that the vehicles are warned timely ($\tau_{MM} \leq \tau_{dl}$). Since CAMs/BSMs are broadcasted, propagation delay is related to the distance to the source. Three-state DCC mechanisms enhance the No DCC performance in terms of providing a reliable performance also for highly-loaded scenarios (up to 400 vehicles), and improving the dissemination of e-safety information. But the final goal of making the performance robust to the variable traffic densities is not achieved. The next action to go for is to design a DCC mechanism, which achieves a dependable performance, i.e. makes the aforementioned transient state shown in the reliability indicator graph in Fig. 5.24 disappear.

The author will redesign the DCC mechanism, making the evolution from state to state more progressive, so that the system is capable of coping with the varying traffic density, without losing reliability.

In addition, variable message inter-arrival time is implemented. ETSI defines that the periodicity of safety-related messages (CAMs and DENMs) is set depending on the vehicle dynamics. A CAM can be transmitted with $1 - 10\ Hz$ update rate, whereas a DENM can be transmitted with $1-20$ Hz [70]. The facilities layer, which resides on top of the transport layer in the OSI model, is in charge of generating these safety-related messages. In between $1 - 10$ Hz a CAM is generated when one of the following criteria is fulfilled since last CAM generation:

- the vehicle has moved more than 4 m,
- the vehicle has changed heading more than 4 degrees, or
- the vehicle has changed speed more than 0.5 m/s.

The author proposes to change the CAM generation rate also when the channel load increases. If the channel load grows and the message generation rate does not change, it leads to a significative number of vehicles backing-off as the channel is sensed busy. This effect impoverishes the overall system performance. On the contrary, the decrement of this rate leads to lower channel access delays and hence lower MAC-to-MAC delays (τ_{MM}) suffered by the broadcasted safety information.

The next approach is a multistate active DCC mechanism implementing transmit power control (TPC) and transmit rate control (TRC) utilities using CST=-90 dBm.

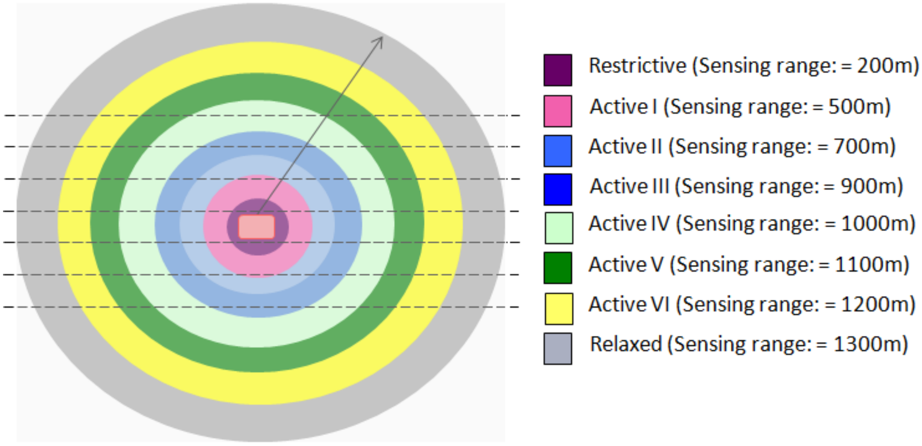

Figure 5.25: TPC design for CST=−90 dBm

The TPC is driven by the measured channel load (CL). Using the same physical layer model as in Section 5.3, the sensing range of a vehicle is divided into eight different zones. These are selected after having simulated the channel loads for all possible transmit powers defined in the standard [10] for dense traffic ($15 \leq \rho \leq 25$ vehicles/km). Same channel loads are grouped in different states, as shown in Fig. 5.25. Finally the groups are assigned a transmit power and also different channel load values are selected as transitions from state to state. The upwards transitions are calculated as $CL_{UP} = \frac{t(P_{RCVD})>CST)}{1\ s}$ and the downwards transitions are calculated as $CL_{DOWN} = \frac{t(P_{RCVD})>CST)}{5\ s}$.

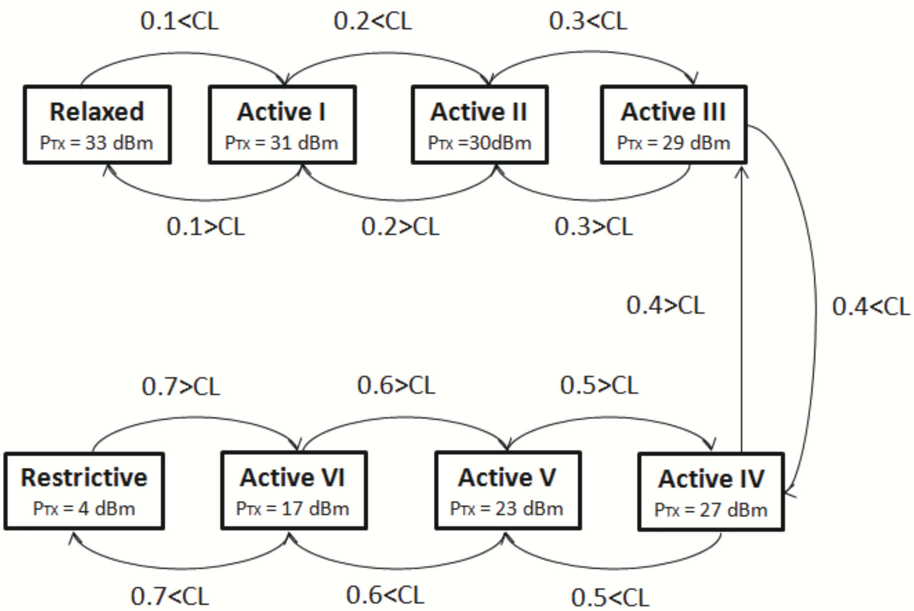

Figure 5.26: Multistate active DCC Mechanism design for $CST = -90\ dBm$

The TRC is implemented based on the centesimal of the channel load. CAM generation rate is decreased from 10 to 1 Hz as the centesimal of the channel load increases.

The curves showing the emergency range evolution (for a QoS (0.9,100 ms)) in time implementing DCC mechanisms show stepwise form, related to the state transitions depending of the common perception of the channel load. For a vehicle initialized in *relaxed state*, using the three-state DCC mechanism introduced in Section 5.3, three different levels are drawn within 86 m and 146 m. Besides, multistate levels fall within 60 m and 120 m emergency range values. The achieved distances at every step are related to the transmit power and the collision probability. The current multistate active approach provides a more stable coverage ranges. Its sustainability in time is an effect of using variable CAM message generation rate. Coverage range is never narrower than 60 m. On the contrary, it fluctuates, strongly for the No DCC case and slightly for the three-state design.

The curves rendering the emergency range evolution for a vehicle initialized in *active state* are similar to the results of the one initialized in *relaxed state*. The performance of a vehicle initialized in *restrictive state*, reflects how the multistate design enhances the performance of plain EDCA and three-state DCC approach, regarding emergency coverage range. It provides higher peaks, which turns into better dissemination of the warnings, (i.e. information is spread over a wider area), and also provides a more stable coverage range within the maximum values, i.e. in a dense traffic situation.

From the analysis of individual node performance in time, the results of the multistate active DCC design using CST=−90 dBm are not very promising at first sight. It outperforms the No DCC and the three-state DCC mechanism proposed by the author, only for a vehicle is initialized in *restrictive state* (namely the most problematic user profile as shown in the previous section). This means that for larger vehicle densities the multistate active DCC adapts smoothly in comparison to the author's three-state DCC. Nevertheless, when a vehicle is initialized in *relaxed state* or *active state* the multistate approach does not adapt efficiently enough to outperform the three-state DCC approach.

And when evaluating the overall system performance, the reliability indicator, results depict how the multistate active DCC approach, which implements transmit power control and transmit rate control, shows the same transient effect present in Section 5.3. The first gap is an accumulative effect of the vehicles since the merging begins until both VANETs are totally merged. And the second one is the same accumulative effect since both VANETs are merged until both VANETs are separated. This gap relates to the performance indicator defined in Section 4.4, $t_{stab} = 36$ s.

In conclusion, reliability is achieved at lightly varying vehicle densities (i.e. t=60 s) but it does not hold during the transition from 200 vehicles VANET to 400 vehicles.

There are two ways to go for enhancing multistate active DCC performance: either (1) to make the state granularity as high as for the earlier states (Fig. 5.25 shows more steps as the transmit power decreases) as it is for the later ones or (2) to make the whole design more robust against vehicle traffic density variation. Both attempts have benefits and drawbacks. The first solution is a more accurate design, but this sensitivity also might lead to neighbour vehicles being in different states, which turns into higher probability of collisions. The second solution relies on increasing the CST for the sake of robustness. But setting it too high might make the DCC lose adaptability to a rapidly changing vehicular scenarios. The author has chosen the second option based on the results from Fig. 5.18, which pointed out that a CST threshold of −90 dBm might be too sensitive for such for strongly varying vehicular density scenarios.

The key goal at this point is to adapt the sensitivity so that the reliable performance is not lost during traffic density variations. For that purpose a more conservative value is selected for the carrier sensing threshold parameter CST=−85 dBm, but still not increasing it that much that the collision probability amongst closely located nodes increases. The aim is to select a CST value where carrier sensing range is decreased for reliability sake.

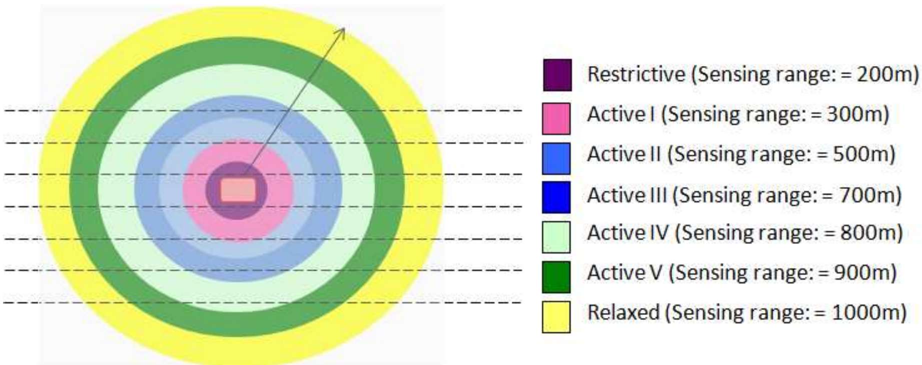

Figure 5.27: TPC design for CST=−85 dBm

The methodology for designing the new multistate active DCC mechanism is the same as before: first an output power level sweep is carried out using a suitable physical model for V2V communication, in order to obtain the transmit power control design shown in Fig. 5.27. Then CL_{UP} and CL_{DOWN} transition values are calculated and a transmit power is assigned to each state, as depicted in Fig. 5.28. And finally on the subject of the transmit rate control, it is inherited from the previous proposal, i.e. it relies on the common perception of the channel load.

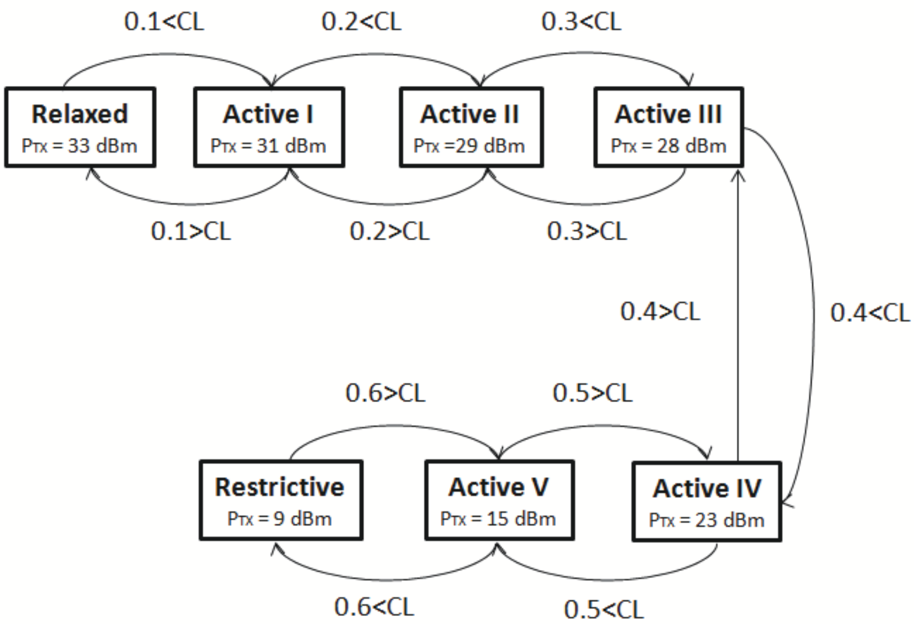

Figure 5.28: Multistate active DCC Mechanism design for CST=−85 dBm

The procedure to study the results is parallel to the one described in Section 5.3, where first an individual node performance study is carried out and then the overall system performance. The performance indicators for studying the individual node work were defined in Chapter 4: the CDF of the MAC-to-MAC delay of each generated CAM message, the emergency coverage range (PPR, Deadline (ms)) of (0.9,100 ms) and the emergency coverage probability for No DCC, multistate active DCC proposal using CST=−90 dBm and the current multistate active DCC proposal. Two new performance indicators (PIs) are added: mean freshness and freshness colour distribution, introduced in Section 4.6. These two PIs show the relevance of the safety-data traffic.

5.4.1 Individual Node Performance

The results of emergency range evolution for a vehicle initialized in *relaxed state* (in Fig. 5.29), show that the new multistate active DCC approach curves fall between the No DCC and the multistate active DCC for CST=−90 dBm. The stepwise pattern is identified and lower peaks are depicted. These lower maximums show how the reference vehicle goes through less number of states. The expected behaviour in terms of reliability is that, for this new multistate active DCC design using CST=−85 dBm, it will not drop below the $CDF(\Delta t)$ level threshold of %90 throughout the whole simulation time.

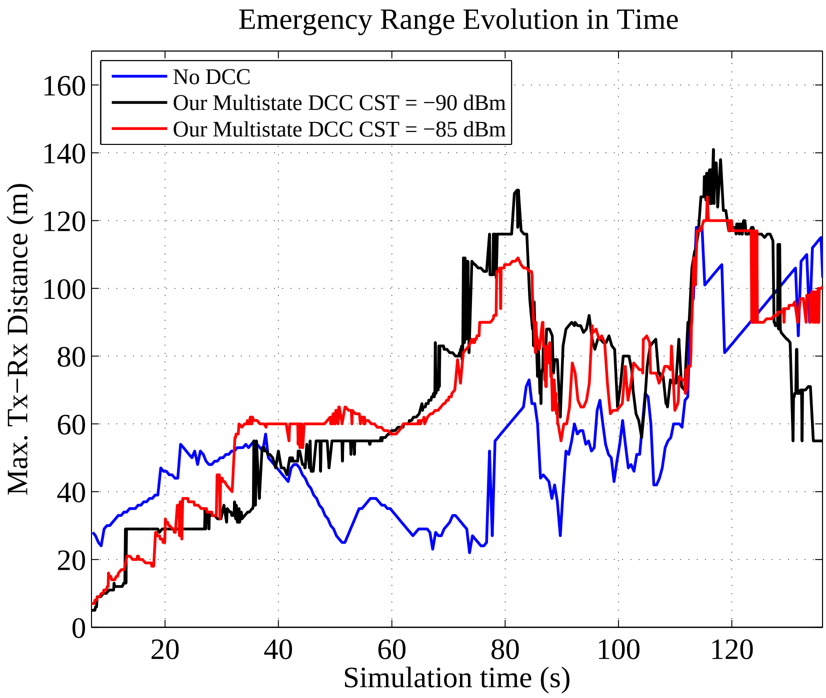

Figure 5.29: Emergency Range vs Simulation Time for a Vehicle initialized in *Relaxed State* for CST=−85 dBm

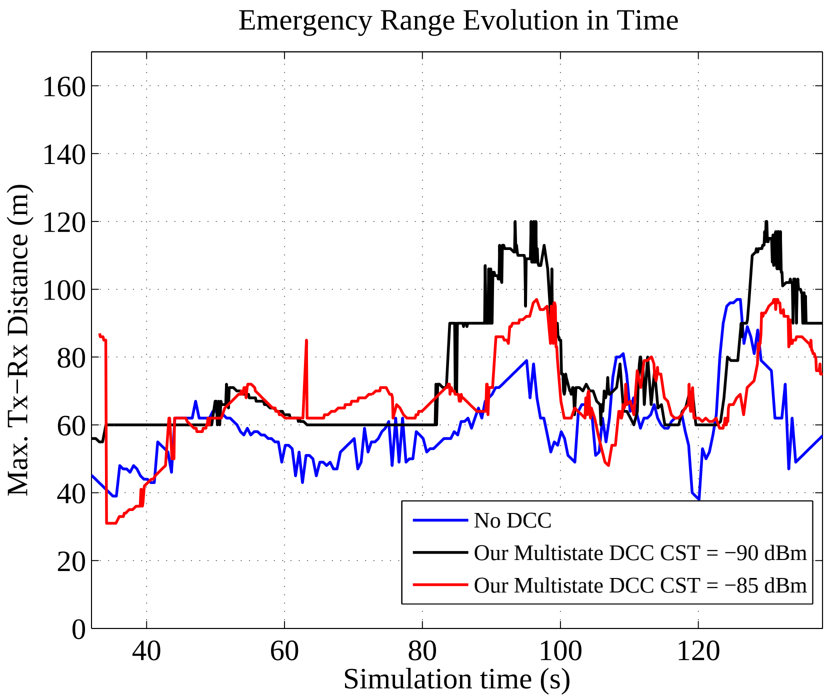

Figure 5.30: Emergency Range vs Simulation Time for a Vehicle initialized in *Active State* for CST=−85 dBm

The curves for a vehicle initialized in *active state* are depicted in Fig. 5.30. Results are less fluctuating than the ones rendered in Fig. 5.29, due to the more stable traffic scenario surrounding the reference vehicle. Maximum peaks are tamed, falling lower than the multistate active DCC proposal using CST=−90 dBm. So greater dependability is expected.

And the last curves referring to a vehicle initialized in *restrictive state*, show a maximal enhancement in terms of coverage range of 10 m in comparison to the plain EDCA case. During the whole merging process, No DCC and the multistate active DCC proposal using CST=−85 dBm follow a similar fashion. The most significative enhancements achieved by the multistate active DCC proposal using CST=−85 dBm take place during the merging and separating, i.e. there when the vehicular traffic density is more variable.

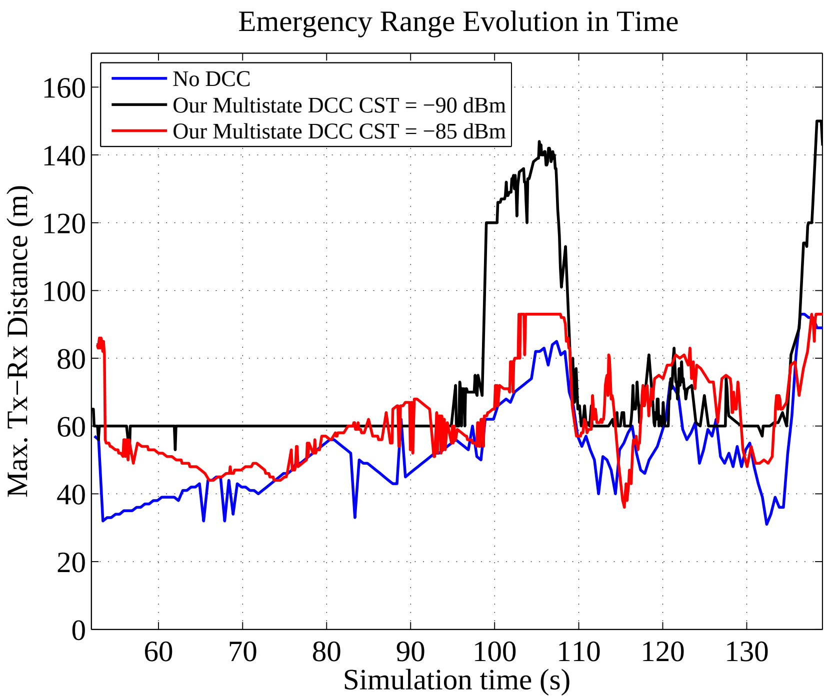

Figure 5.31: Emergency Range vs Simulation Time for a Vehicle initialized in *Restrictive State* for CST−85 dBm

Before merging

Fig. 5.32 displays the results for a vehicle initialized in *relaxed state* at t=60 s. It shows how the current DCC outperforms the No DCC and the multistate active DCC using $CST = -90\ dBm$. It reaches a reliable performance without sacrificing much coverage range in comparison to the other multistate design (Tab. 5.17). Comparing the results to the ones achieved by author's three-state DCC collected in Tab. 5.9, the current multistate active DCC proposal achieves the same results in terms of CDF(Δt), and loses 26 m Δd. However, 24 m coverage range enhancement seems fair enough for safety information dissemination.

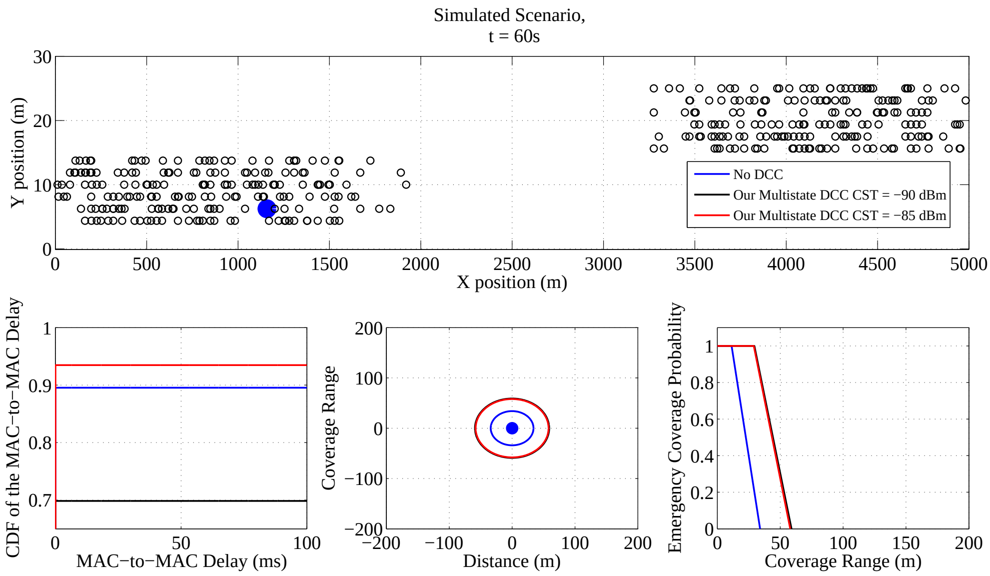

Figure 5.32: Simulation Results for a Vehicle initialized in *Relaxed State* ($t = 60\ s$) for CST−85 dBm

Table 5.17: Simulation Results (CDF(Δt),Δd) for a Vehicle initialized in *Relaxed State* (t=60 s) for CST−85 dBm

	(CDF(Δt),Δd)
No DCC	(0.89, 34 m)
Multistate active DCC proposal $CST = -90\ dBm$	(0.7, 59 m)
Multistate active DCC proposal $CST = -85\ dBm$	(0.93, 58 m)

The performance of a vehicle initialized in *active state*, presents that both DCC mechanisms have similar results in terms of CDF(Δt) and Δd. And thank to the use of either of the DCC mechanisms, reliability threshold is achieved.

In comparison to author's three-state DCC collected in Tab. 5.10, the current multistate active DCC proposal achieves the same results in terms of CDF(Δt), and loses 14 m Δd. Yet, a coverage range of 63 m is suitable for CAM dissemination.

Table 5.18: Simulation Results (CDF(Δt),Δd) for a Vehicle initialized in *Active State* (t=60 s) for CST−85 dBm

	(CDF(Δt),Δd)
No DCC	(0.87, 55 m)
Multistate active DCC proposal $CST = -90\ dBm$	(0.97, 63 m)
Multistate active DCC proposal $CST = -85\ dBm$	(0.97, 63 m)

And for the first time in all the previously presented simulations, the performance of a vehicle initialized in *restrictive state* reaches a reliable performance using the current multistate active DCC proposal. In contrast to the No DCC performance, due to the multistate active DCC (using CST−85 dBm) implementing TPC and TRC, both reliability and coverage range are enhanced, as shown in Fig. 5.33. Tab. 5.19 underlines up to 0.07 and 12 m enhancement, CDF(Δt) and Δd respectively.

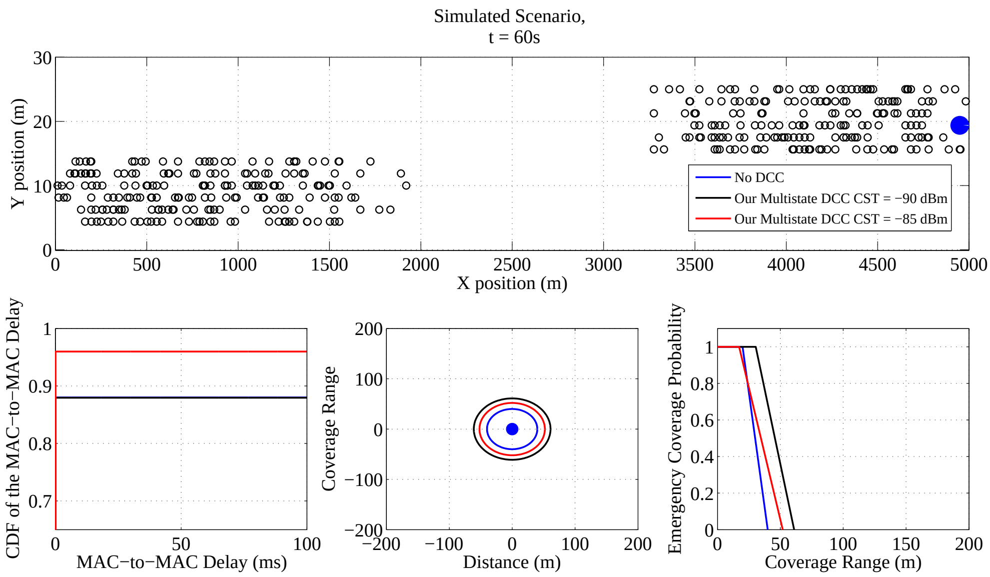

Figure 5.33: Simulation Results for a Vehicle initialized in *Restrictive State* (t=60 s) for CST−85 dBm

Table 5.19: Simulation Results (CDF(Δt),Δd) for a Vehicle initialized in *Restrictive State* (t=60 s) for CST−85 dBm

	(CDF(Δt),Δd)
No DCC	(0.88, 40 m)
Multistate active DCC proposal $CST = -90\ dBm$	(0.87, 61 m)
Multistate active DCC proposal $CST = -85\ dBm$	(0.95, 52 m)

Merging

The results obtained from the performance analysis of a vehicle initialized in *relaxed state* during the merging of the two internally self-organized VANETs are shown in Fig. 5.34. Just the current multitstate approach reaches a reliable performance and and Tab. 5.20 ilustrates how in comparison to the multistate active DCC proposal using CST=−90 dBm, by losing 14 m of coverage range, an increment of 0.07 in reliability is reached. In contrast to the No DCC both terms, reliability and coverage range, are enhanced by using the current multistate active DCC proposal. Comparing the results to the ones achieved by author's three-state DCC collected in Tab. 5.12, the current multistate active DCC proposal achieves the same results in terms of CDF(Δt), and loses 30 m Δd (similar differential performance as *before merging*).

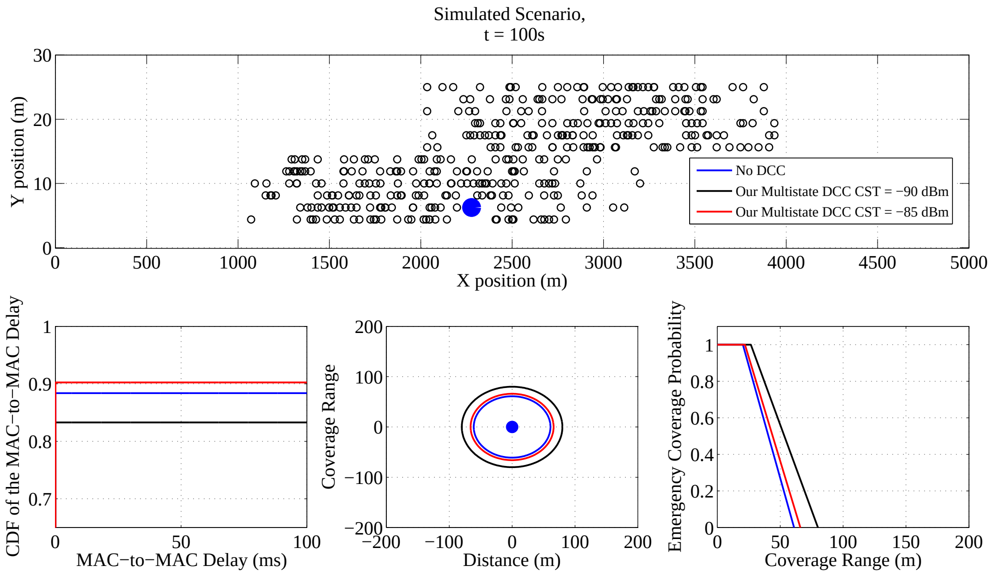

Figure 5.34: Simulation Results for a Vehicle initialized in *Relaxed State* (t=100 s) for CST−85 dBm

Table 5.20: Simulation Results (CDF(Δt),Δd) for a Vehicle initialized in *Relaxed State* (t=100 s) for CST−85 dBm

	(CDF(Δt),Δd)
No DCC	(0.87, 61 m)
Multistate active DCC proposal $CST = -90\ dBm$	(0.83, 80 m)
Multistate active DCC proposal $CST = -85\ dBm$	(0.9, 66 m)

The results in Tab. 5.21, related to a vehicle initialized in *active state*, displays similar results to the ones in Tab. 5.20. In comparison to the results in Section 5.3, the coverage ranges have not increased from the use case of a vehicle initialized in *relaxed* to *active state* influenced by the higher traffic density in the surrounding of the latter reference vehicle. In this case, because of the lower setting of the CST to −85 dBm, the coverage range is more robust to the varying traffic density.

Table 5.21: Simulation Results (CDF(Δt),Δd) for a Vehicle initialized in *Active State* (t=100 s) for CST−85 dBm

	(CDF(Δt),Δd)
No DCC	(0.86, 58 m)
Multistate active DCC proposal $CST = -90\ dBm$	(0.81, 86 m)
Multistate active DCC proposal $CST = -85\ dBm$	(0.91, 67 m)

The last use case is the performance of a vehicle initialized in *restrictive state*. Once again the current multistate active DCC also outperforms the plain EDCA and the multistate active DCC proposal using $CST = -90\ dBm$. Reliability is achieved CDF(Δt)=0.93 and the No DCC coverage range is enlarged up to 5 m (see Tab. 5.22).

Table 5.22: Simulation Results (CDF(Δt),Δd) for a Vehicle initialized in *Restrictive State* (t=100 s) for CST−85 dBm

	(CDF(Δt),Δd)
No DCC	(0.83, 67 m)
Multistate active DCC proposal $CST = -90\ dBm$	(0.85, 127 m)
Multistate active DCC proposal $CST = -85\ dBm$	(0.93, 72 m)

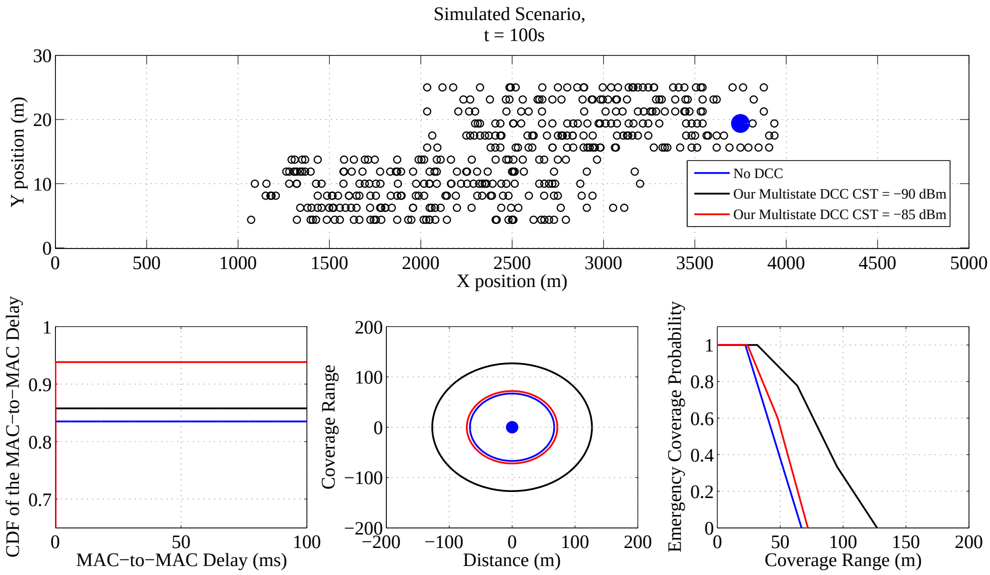

Figure 5.35: Simulation Results for a Vehicle initialized in *Restrictive State* (t=100 s) for CST−85 dBm

After merging

And lastly, in the after merging use case, the current multistate active DCC design masters the rest of the performance for all the three studied profiles (a vehicle initialized in *relaxed, active and restrictive state*).

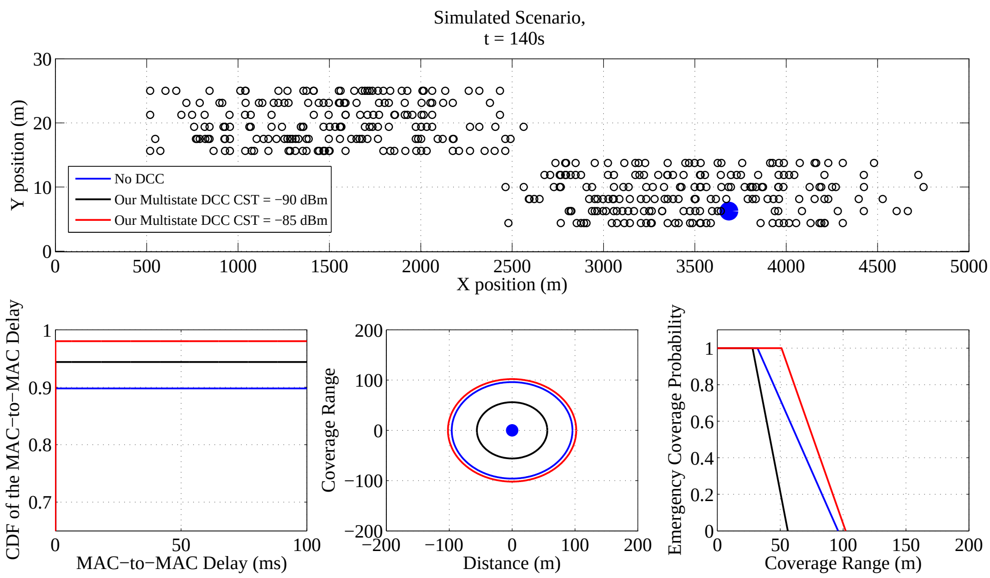

Figure 5.36: Simulation Results for a Vehicle initialized in *Relaxed State* (t=140 s) for CST−85 dBm

Table 5.23: Simulation Results (CDF(Δt),Δd) for a Vehicle initialized in *Relaxed State* (t=140 s) for CST−85 dBm

	(CDF(Δt),Δd)
No DCC	(0.89, 96 m)
Multistate active DCC proposal $CST = -90\ dBm$	(0.94, 56 m)
Multistate active DCC proposal $CST = -85\ dBm$	(0.98, 102 m)

For the vehicle initialized in *relaxed state* the current multistate active DCC approach enhances both, reliability and coverage range, for No DCC and the multistate active DCC proposal using $CST = -90\ dBm$ (see Tab. 5.23). On the other hand, Tab. 5.24 displays the results for a vehicle initialized in *active state*, and it reflects how reliability can be enhaced (from DCC to DCC design) to the cost of coverage range. Still, both DCC mechanisms achieve a reliable performance. In comparison to No DCC, the current multistate active DCC mechanism shows an increment on the reliability (0.08) and on the coverage range (29 m).

Table 5.24: Simulation Results (CDF(Δt),Δd) for a Vehicle initialized in *Active State* (t=140 s) for CST−85 dBm

	(CDF(Δt),Δd)
No DCC	(0.89, 54 m)
Multistate active DCC proposal $CST = -90\ dBm$	(0.95, 91 m)
Multistate active DCC proposal $CST = -85\ dBm$	(0.97, 85 m)

And for the vehicles initialized in an already heavy-loaded scenario, therefore having the more conservative initial parameter setting (vehicles initialized in *restrictive state*), the current multistate outperforms the rest but reliability threshold is not yet achieved, as shown in Fig. 5.37 and in Tab. 5.25.

Table 5.25: Simulation Results (CDF(Δt),Δd) for a Vehicle initialized in *Restrictive State* (t=140 s) for CST−85 dBm

	(CDF(Δt),Δd)
No DCC	(0.85, 94 m)
Multistate active DCC proposal $CST = -90\ dBm$	(0.67, 115 m)
Multistate active DCC proposal $CST = -85\ dBm$	(0.86, 77 m)

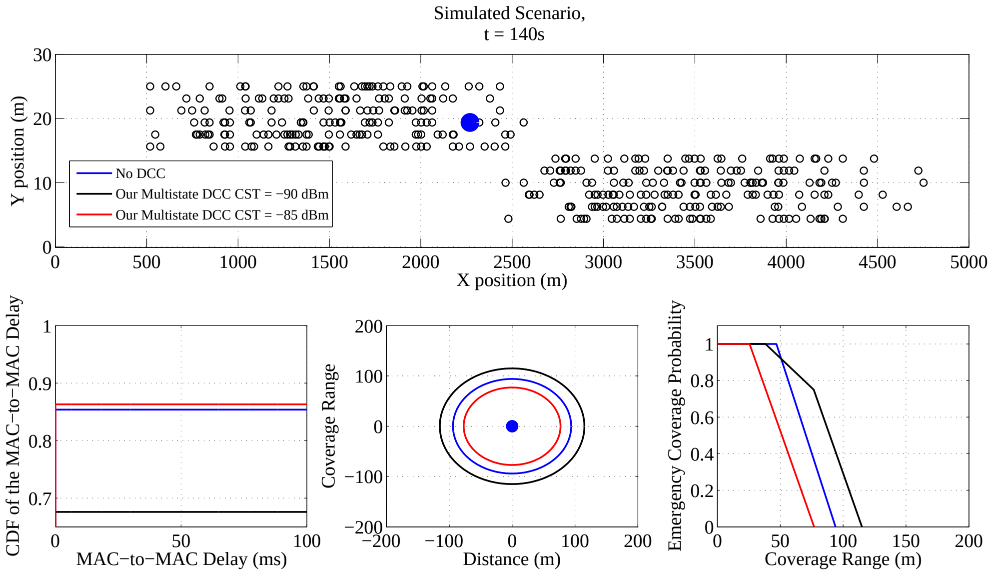

Figure 5.37: Simulation Results for a Vehicle initialized in *Restrictive State* (t=140 s) for CST−85 dBm

5.4.2 VANET Performance

Overall system results present the performance in terms of reliability and dependability.

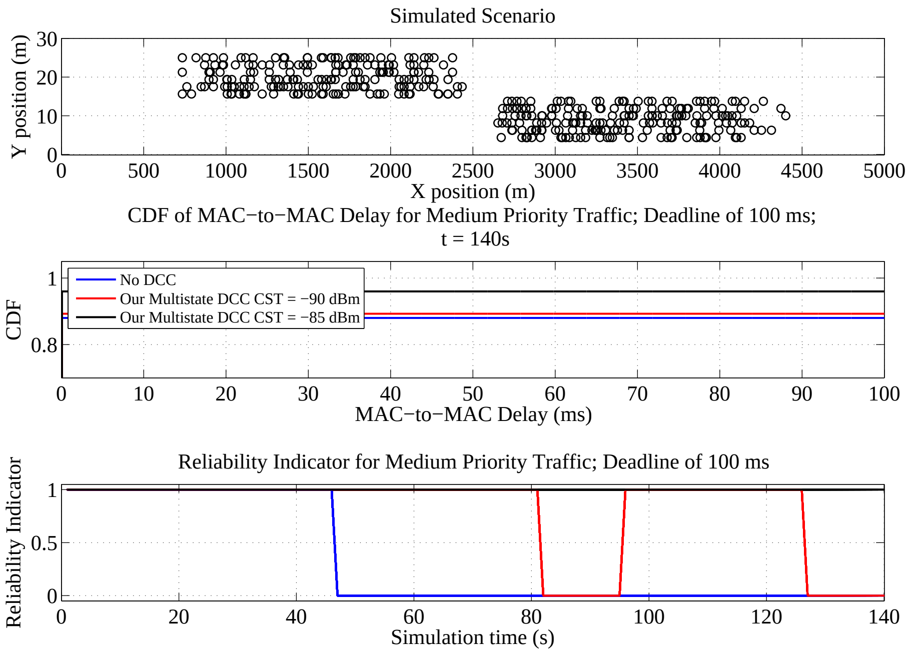

Figure 5.38: System Performance for two VANET merging scenario: CDF of MAC-to-MAC Delay and Reliability Indicator for $CST = -85\ dBm$

Reliability is achieved, i.e. CDF(Δt) has reaches the 0.9 threshold and maintained in time above it, regardless of the vehicular traffic density fluctuations.

The next VANET performance results are related to the value of the broadcasted data. By freshness in meant the "age" (validity time, since is generated until is handed out) of the messages present in the VANET and its evolution in time. For safety-related data it is very important that the broadcasted data is as contemporary as possible, i.e. the transmissions are most up-to-date. The plain EDCA and three-state design have fixed message generation rate set to 2 Hz, whereas the two multistate approaches implement TRC. As Fig. 5.39 shows, the mean freshness for the multistate designs is lower and similar to each other (as both implement the same TRC). This means that the broadcasted data traffic is *fresher*.

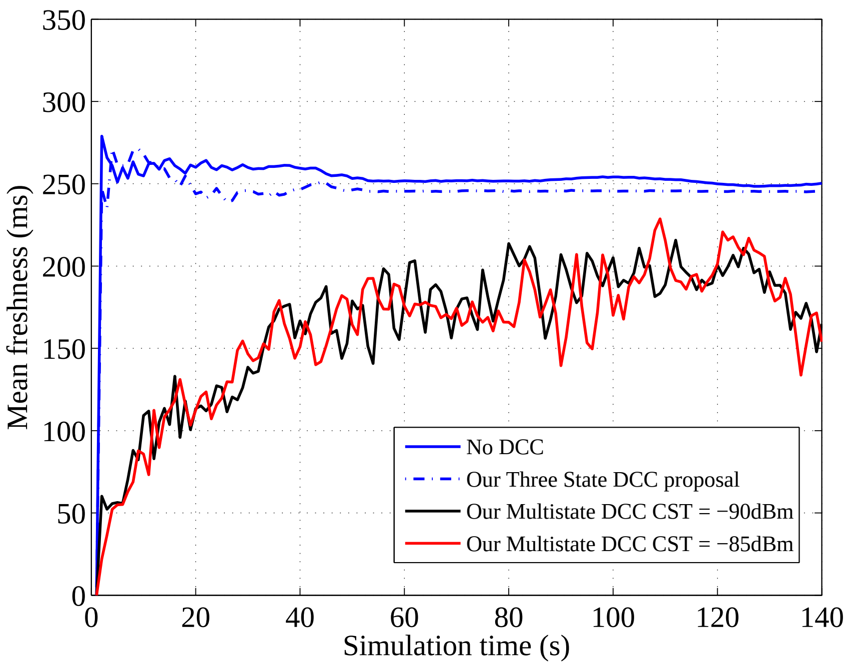

Figure 5.39: System Performance for two VANET merging scenario: Mean Freshness

Finally the freshness values are classified in five colours. When the freshness is,

- lower or equal to 100 ms,
- between 100 ms and lower or equal to 200 ms,
- between 200 ms and lower or equal to 300 ms,
- between 300 ms and lower or equal to 400 ms and
- between 400 ms and lower or equal to 500 ms.

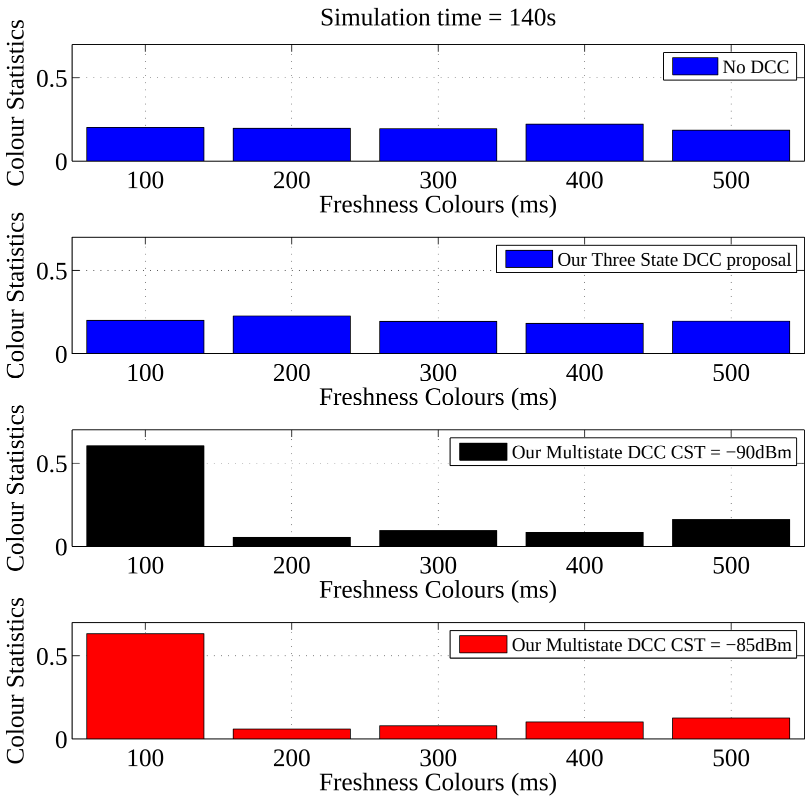

Figure 5.40: System Performance for two VANET merging scenario: Freshness colours at $t = 140\ s$

For fixed message generation rate the freshness distribution throughout the colours is homogeneously distributed. However, for variable message generation rate, it is exponentially distributed, exponentially decaying from 100 ms to 500 ms. A function could be approximated to this distribution. It could be used to compare different TRC implementations.

6

Conclusions

This thesis provides the following main contributions in the field of MAC protocols in vehicular communications for scheduling e-safety data traffic: firstly, the analytical description for the collision probability of IEEE802.11p MAC and the alternative, SoTDMA. This formulation was the missing cornerstone for evaluation and validation of MAC protocol simulation tools in vehicular communications. Secondly, this work proposes new performance indicators for MAC performance when scheduling safety-related data traffic. And thirdly this thesis has applied the aforementioned methodology to the performance study of various transient vehicular scenarios.

My overall conclusions are that the IEEE802.11p MAC has a lower *mean* channel access delay, whereas SoTDMA (which is proven to be feasable in real-world vehicular environments) is more *predictable* and has a better *reliability* in terms of delay in heavily-loaded scenarios with variable traffic density. SoTDMA can be used as a benchmarking reference in start-up scenarios, as it outperforms CSMA/CA. In this sense, SoTDMA defines a benchmark level which is achievable by IEEE802.11p MAC only when EDCA is used and the traffic priority is tuned. For initially dense scenarios (with vehicle inter-arrival time 1 s) and dynamic scenarios with variable traffic density (i.e. merging scenarios), the use of SoTDMA and plain EDCA is discouraged. In both scenarios, reliability is lost during the merging. For EDCA, even the performance for a 200 vehicles VANET turns out to be unreliable. Reliability in terms of delay and coverage range is guaranteed through the implementation of an additional crosslayer enhancement (the so called DCC mechanism). Moreover, dependability is achieved throughout the whole simulation time.

6.1 Key Performance Indicators

When scheduling safety-related information it is very important that warnings arrive timely and that they are disseminated as far as possible from the source, so the drivers can anticipate the danger. In previous work reliability has been evaluated only in terms of the *cumulative distribution function of the MAC-to-MAC delay ($CDF(\Delta t)$)*. This thesis has presented the complementary information showing the dissemination range (Δd) and the reliability in terms of *complementary cumulative distribution function of the coverage range (($CCDF(\Delta d)$))*. The tuple ($CDF(\Delta t), \Delta d$) provides a complete description of the reliability. Also by evaluating the temporal evolution of a reliability indicator, a dependability indication is obtained. Instead of instantaneous performance, a QoS performance study has been carried out.

Further, this work has also provided performance indicators for evaluating the TRC algorithm within the DCC mechanism (*freshness of the information*). My results show that the "fresher" the information, the better the TRC works, as opposed to no TRC.

Finally, as the evaluated scenarios are transient, the *stabilization time* has been used to provide an indication of the time required for regaining a reliable performance in varying vehicular traffic density scenarios. Results have shown that using the DCC mechanism in scenarios with significantly changing traffic density, reliability is sustained for a longer time until an accumulative effect in a merging scenario occurs. It is evaluated as *stabilization time* depending on the size of each individual VANET and the speeds of the platoons. This key performance indicator is useful for short-term evolution estimation for the road network.

6.2 Performance of MAC Layer for Traffic-Safety

Previous work [29] has proven that CSMA/CA (the MAC algorithm of the IEEE802.11p) is outperformed by the SoTDMA (inherited MAC algorithm from the AIS of the ship industry) in stable highly-loaded scenarios when scheduling broadcasted safety messages. The slotted-based approach is advantageous for being very predictable and always providing channel access regardless of the channel load. This thesis implemented initially a simplified SoTDMA in order to study the feasibility of using it in real vehicular environments. The results have shown how four vehicles actively join the network at different time instants. The vehicles deterministically select the time slot for transmission based on the information acquired when receiving the first frame. Next, they start transmitting CAM messages periodically without collisions. These results validate that a cooperative awareness service could be provided in a real vehicular scenario.

Once proved that SoTDMA is feasible, challenging vehicular scenarios were defined in order to evaluate the performance in transient state VANETs. These scenarios are highly-loaded vehicular scenarios where the traffic density is rapidly changing. A full implementation of both MAC algorithms has been achieved in the Matlab language and two selected scenarios have been evaluated: (1) start-up phase of a VANET and (2) merging of two VANETs.

The simulation results of a VANET in start-up phase show that for up to 400 vehicles the $CDF(\Delta t)$ level reaches 0.8 when using CSMA/CA. SoTDMA outperforms this level by achieving 0.85. Only when switching to EDCA (which defines a set of QoS enhancements for wireless LAN applications through modifications to the MAC layer) and changing the AIFS and CW size (i.e. lowering the priority), IEEE802.11p results improve and reach the SoTDMA benchmarks. In this scenario the collision probability is the dominant loss contribution. In addition, these results have been validated via the analytical descriptions in Chapter 4. For the purposes in this thesis, the reliability threshold is defined as the 90% percentile of the MAC-to-MAC delay, i.e. the delay Δt where the $CDF(\Delta t)$ level surpases 0.9. Consequently, neither CSMA/CA nor SoTDMA achieve the reliability threshold 0.9 when using constant transmit power. This failure motivates investigations into the DCC mechanism, as an enhancement of the IEEE802.11p MAC in heavily-loaded scenarios.

The last scenario evaluated in this thesis is the merging scenario of two internally well-organized VANETs. The impact of traffic density variation is studied. Both EDCA and SoTDMA display unreliable performance when the vehicle density changes from 200 to 400 vehicles (for a initially dense VANET, i.e. vehicle inter-arrival time is lower than 3 s). The DCC mechanism is introduced in order to reach a reliable and dependable performance. The best results are achieved when the transmit power control states are designed in relation to the channel load (a.k.a channel busy ratio (CBR)). Using the proposed transmit rate control, a more reliable performance is achieved by using a multistate active DCC design. Still when merging occurs (200 to 400 vehicles within range are detected) the overall system performance requires a some stabilization time until reliable performance is regained. When both VANETs begin to separate, the transient effect reappears. These accumulative effects in transient vehicular scenarios are eased by sharing the information of the joint channel perception (e.g. individual perception of the channel load or collision probability). By these means vehicles synchronize to set a common parameter setting (make a joint decision) so that the overall VANET performance is enhanced. Alternatively, the carrier sensing threshold (CST) can be tuned.

This work discusses the results for this second option. The simulation results show that dependability is reached only when the CST sensitivity is increased to −85 dBm. With that parameter setting, coverage ranges are enhanced by 5 to 10 m in comparison to plain EDCA performance, reaching 60 to 100 m coverage ranges for a QoS (0.9,100 ms).

The dependence of the MAC performance on the vehicle inter-arrival time is an important effect. This has a significant impact on the MAC performance, particularly on the collision probability. This work presents results setting the inter-arrival time to zero (during the start-up phase of a VANET, i.e. vehicles are initialized within the same frame), and in that situation the reliability is lost. In the case of SoTDMA this behaviour holds until the inter-arrival time is set to 3 s which means that all the vehicles in the vicinity of the reference are sensed (there are no collisions for the same channel perception between vehicles within range). The large number of collisions for small inter-arrival times turns out to be a drawback of SoTDMA. EDCA is less sensitive to this parameter. Still, results have shown that using an inter-arrival time lower than 3 s not even a 200 vehicle VANET performs reliably. Therefore, it is concluded that a DCC mechanism is required for the sake of robustness.

ETSI defines a message transmit rate variability depending on the driving behaviour. Additionally, this thesis proposes to implement TRC in case of heavily-loaded scenarios in order to ease the channel load as the number of vehicles increases. The SoTDMA algorithm defines that the vehicle shall exit the *continuous operation* phase and restarts the scheduling algorithm if the message report interval is changed. Thus, the vehicle reenters the *initialization phase* and listens to the activity of the whole frame. Next, the vehicle enters the *network entry* phase, *first frame* and finally the *continuous operation*. This induces a skip in the transmission during its *initialization phase* each time the transmit rate changes. This behaviour is clearly unsuitable for safety-related messages. For this reason, SoTDMA is useful for benchmarking other protocols. However, it is less suitable for rapidly changing vehicular scenarios (with variable transmit rates) and scenarios with variable vehicular traffic density.

7

Future Work/Outlook

The next steps to take regarding the research topic of of medium access control algorithms in the field of vehicular communications, when scheduling safety-related data are easy to surmise. From the simulation point of view the main element the researchers are lacking of is a suitable PHY model for the vehicular channel. Even if the theoretical models to be used are there, a suitable parametrization is still to be defined. For that purpose measurement campaigns and analytical evaluation of results should be carried out in order to obtain useful values to tune the MAC layer simulators, such as sensing ranges and coverage ranges for different transmit powers or for different CST values. That would be very useful for further DCC design. Also as mentioned in the previous chapter, cooperation amongst vehicles leads to overall VANET performance enhancement, as vehicles can synchronize to set a common parameter settings (make a joint decission based upon the treatment on the joint information gathered from the neighbours). This might decrease the collision probability.

Regarding the outlook, there are still some questions open in this area of knowledge. On one side, SoTDMA was thought for time-driven messaging. Not only for stable but also for transient traffic scenarios it outperforms EDCA. SoTDMA performance could benefit from implementing an additional crosslayer enhancement, similar to the DCC mechanism, or applying carrier-sensing. But due to commercial aspects it is not so straightforward to go for this implementation. Would the migration from EDCA to SoTDMA be feasable? And the cohabitation of vehicles implementing either of them? Theoretically if the number of nodes using SoTDMA would increase, these vehicles would push EDCA nodes back, as they would transmit when scheduled and would not back-off until channel is sensed idle. So cohabitation would be possible.

The next question is that if EDCA and SoTDMA would be used depending on the scenario or the application data to be managed (i.e. in SCH and CCH respectively), is it feasable an implementation of those two MAC schemes on one equipment? In the author's opinion the solution would be either to go for two transceivers (one for CCH and other for SCH) or have a switch (like the US channel switching). Still within the topic of SoTDMA as an alternative MAC for safety-related data, this work has studied lightly-loaded and heavily loaded scenarios. Results have shown that the earlier case, which can be related to a urban scenario (up to 50 vehicles), is not that struggling for IEEE802.11p MAC. The channel is sensed idle often enough to provide a lower channel access delay than SoTDMA. Regarding corner effects, that would not affect the performance, due to the fact that IEEE802.11p is defined for the 5.9 GHz carrier frequency. But it is in highway scenarios (i.e. heavily loaded) when SoTDMA is more advantageous due to its structured access and predictable performance. On the other side, multihop is another open issue in order to enhance the dissemination of safety messages. CAMs/BSMs are one hop messages but some ideas have arisen about the possibility of DENMs being disseminated via multihop. Applications such as geonetworking push in that direction. Another hot topic are the geonetworking algorithms. They are based on flooding approach to transmit each data packet to all reachable nodes within the geocast region. But as safety-related messages are sent via CCH, it is not recomended to do multihop in order not to overload the channel. So it is encouraged that geocasted data is not transmitted on the CCH but on the SCH. And finally in order to enhance the reliability, network coding is thought to be an option. In the work carried out so far, it has been proven to perform correctly just in slow speed vehicular environments. Still this is an aspect to have a look into.

Acronyms

AC Access Categories
AC BE Access Category Best Effort
AC VI Access Category Background
ACK Acknowledgement
AC VI Access Category Video
AC VO Access Category Video
AIFS Arbitration Inter-Frame Space
BSM Basic Safety Message
CACS Comprehensive Automobile Traffic Control System
CAM Cooperative Awareness Message
CALM Communication Architecture for Land Mobiles
CBR Channel Busy Ratio
CCA Clear Channel Assessment
CCF Control Under Fairness Constraints
CCH Control Channel
CCDF Complementary Cumulative Distribution Function
CDF Cumulative Distribution Function
C-ITS Cooperative intelligent transport systems
CRC Cyclic Redundancy Check
CL Channel Load
CSMA/CA Carrier Sensing Multiple Access/Collision Avoidance
CST Carrier Sensing Threshold
CW Contention Window
DCC Decentralized Congestion Control
DCF Distributed Coordination Function
DENM Decentralized Environmental Notification Message

D-FPAV Distributed Fair Transmit Power Adjustment for Vehicular networks
DSRC Dedicated Short-Range Communication
EDCA Enhanced Distributed Channel Access
ERGS Electronic Route-Guidance System
ETSI European Telecommunication Standards Institute
FCS Frame Check Sequence
FDMA Frequency Division Multiple Access
FER Frame Error Ratio
HCF Hybrid Coordination Function
ISO International Standard Organization
LIMERIC LInear MEssage Rate Integrated Control
LoS Line of Sight
LTE Long Term Evolution
MAC Medium Access Control
MCS Modulation and Coding Scheme
MIMO Multiple Input Multiple Output
MITI Ministry of International Trade and Industry
MPDU MAC Protocol Data Unit
NI Nominal Increment
NS Nominal Slot
NSS Nominal Selection Slot
NTS Nominal Transmission Slot
OFDM Orthogonal Frequency Division Multiplexing
P Transmit Power
PCF Point Coordination Function
PHY Physical Layer
PI Packet Interval
PPR Probability of Packet Reception
PROMETHEUS Program for European Traffic with Highest Efficiency and Unprecedented Safety
QoS Quality of Service
RSU Road-Side Unit
S-Aloha Slotted Aloha
SCH Service Channel
SI Selection Interval
SINR Signal to Interference plus Noise Ratio
SNR Signal to Noise Ratio

SoTDMA Self-Organizing Time Division Multiple Access
TDMA Time Division Multiple Access
TPC Transmit Power Cotrol
TRC Transmit Rate Cotrol
UMTS Universal Mobile Telecommunications System
V2V Vehicle-to-Vehicle
VANET Vehicular ad-hoc Network
WAVE Wireless Access in Vehicular Environments
WiMAX Worldwide Interoperability for Microwave Access
WLAN Wireless Local Area Network
WPAN Wireless Personal Area Network

List of Figures

List of Tables

Bibliography

[1] A. Alonso, D. Smely, and C.F. Mecklenbräuker. Throughput of Self-Organizing Time Division Multiple Access MAC Layer for Vehicular Networks Based on Measured SNR Time-Series. In *Vehicular Technology Conference (VTC Fall), 2011 IEEE*, pages 1–5, 2011.

[2] A. Alonso and C. F. Mecklenbräuker. Stabilization Time Comparison of CSMA and Self-Organizing TDMA for different channel loads in VANETS. In *ITS Telecommunications (ITST), 2012 12th International Conference on*, pages 300–305. IEEE, 2012.

[3] [submitted] A. Alonso and C. F. Mecklenbräuker. Dependability Evaluation of the IEEE802.11p MAC implementing Multistate Active DCC Mechanism. *Wireless Communications, IEEE Transactions on*, 2013.

[4] Standards on Railroad and Vehicular Communications: Methods of Testing, 1949. *Proceedings of the IRE*, 37(12):1372–1375, 1949.

[5] D.C. Pinkerton. Shadows of the future in vehicular communication. *IRE Transactions on Vehicular Communications*, 12(1):27–34, 1959.

[6] D.A. Rosen, F.J. Mammano, and R. Favout. An electronic route-guidance system for highway vehicles. *Vehicular Technology, IEEE Transactions on*, 19(1):143–152, 1970.

[7] E. Guizzo. How Google's Self-Driving Car Works. Online, October 2011.

[8] S. Totani. Development and current status of CACS (comprehensive automobile traffic control system). In *Vehicular Technology Conference, 1980. 30th IEEE*, volume 30, pages 336–341, 1980.

[9] IEEE Standard for Information Technology–Telecommunications and Information Exchange Between Systems–Local and Metropolitan Area Networks–Specific requirements Part 11: Wireless LAN Medium Access Control (MAC) and Physical Layer (PHY) Specifications Amendment 6: Wireless Access in Vehicular Environments. *IEEE Std 802.11p-2010 (Amendment to IEEE Std 802.11-2007 as amended by IEEE Std 802.11k-2008, IEEE Std 802.11r-2008, IEEE Std 802.11y-2008, IEEE Std 802.11n-2009, and IEEE Std 802.11w-2009)*, pages 1 –51, 15 2010.

[10] ETSI ES 202 663: Intelligent Transport Systems (ITS); European profile standard for the physical and medium access layer of Intelligent Transport Systems operating in the 5 GHz frequency band. Technical report, European Telecommunications Standards Institute (ETSI), 2010.

[11] K. Sjöberg. *Medium Access Control for Vehicular Ad Hoc Networks*. PhD thesis, Department of Signals and Sytems Chalmers University of Technology. Gothenburg, Sweden, 2013.

[12] ETSI TS 102 687 (v1.1.1), Intelligent Transport Systems (ITS); Decentralized Congestion Control Mechanism for Intelligent Transport Systems operating the 5 GHz range; Access layer part. Technical report, European Telecommunications Standards Institute (ETSI), 2011.

[13] K. Selvarajah, A. Tully, and P.T. Blythe. ZigBee for Intelligent Transport System applications. In *Road Transport Information and Control - RTIC 2008 and ITS United Kingdom Members' Conference, IET*, pages 1–7, 2008.

[14] ZigBee Alliance. ZigBee specification. *ZigBee Document 053474R13*, pages 344–346, 2006.

[15] M. Constantinescu and E. Borcoci. Optimization method for smart antenna use in WiMAX vehicular communications. In *Communications (COMM), 2012 9th International Conference on*, pages 263–266, 2012.

[16] T. Mangel, T. Kosch, and H. Hartenstein. A comparison of UMTS and LTE for vehicular safety communication at intersections. In *Vehicular Networking Conference (VNC), 2010 IEEE*, pages 293–300, 2010.

[17] G. Araniti, C. Campolo, M. Condoluci, A. Iera, and A. Molinaro. LTE for vehicular networking: a survey. *Communications Magazine, IEEE*, 51(5):148–157, 2013.

[18] S. Shankar and A. Yedla. MAC layer extensions for improved QoS in 802.11 based vehicular ad hoc networks. In *Vehicular Electronics and Safety, 2007. ICVES. IEEE International Conference on*, pages 1–6, 2007.

[19] Y. Qian, K. Lu, and N. Moayeri. A secure VANET MAC protocol for DSRC applications. In *Global Telecommunications Conference, 2008. IEEE GLOBECOM 2008.*, pages 1–5, 2008.

[20] A. Kajackas, A. Vindašius, and Š. Stanaitis. Inter-Vehicle Communication: Emergency Message Delay Distributions. *Electronic and Electrical Engineering.– Kaunas: Technologija*, 8:96, 2009.

[21] S. Makido, N. Suzuki, T. Harada, and J. Muramatsu. Decentralized TDMA protocol for real-time vehicle-to-vehicle communications. *IPSJ Journal*, 48(7):2257–2266, 2007.

[22] A. Mann and J. Ruckert. A new concurrent slot assignment protocol for traffic information exchange. In *Vehicular Technology Conference, 1988, IEEE 38th*, pages 503–508, 1988.

[23] W. Zhu, T. Hellmich, and B. Walke. DCAP, A decentral channel access protocol: performance analysis. In *Vehicular Technology Conference, 1991. Gateway to the Future Technology in Motion., 41st IEEE*, pages 463–468, 1991.

[24] F. Borgonovo, A. Capone, M. Cesana, and L. Fratta. RR-ALOHA, A Reliable R-ALOHA broadcast channel for ad-hoc inter-vehicle communication networks. *proceedings of MedHocNet*, 2002.

[25] F. Borgonovo, A. Capone, M. Cesana, and L. Fratta. ADHOC: A new, flexible and reliable MAC architecture for ad-hoc networks. In *Wireless Communications and Networking, 2003. WCNC 2003. 2003 IEEE*, volume 2, pages 965–970 vol.2, 2003.

[26] R. Scopigno and H.A. Cozzetti. Mobile Slotted Aloha for VANETs. In *Vehicular Technology Conference Fall (VTC 2009-Fall), 2009 IEEE 70th*, pages 1–5, 2009.

[27] Y. Tadokoro, K. Ito, J. Imai, N. Suzuki, and N. Itoh. Advanced transmission cycle control scheme for autonomous decentralized TDMA protocol in safe driving support systems. In *Intelligent Vehicles Symposium, 2008 IEEE*, pages 1062–1067, 2008.

[28] L. G. Roberts. ALOHA packet system with and without slots and capture. *ACM SIGCOMM Computer Communication Review*, 5(2):28–42, 1975.

[29] K. Bilstrup, E. Uhlemann, E.G. Ström, and U. Bilstrup. On the ability of the 802.11p MAC method and STDMA to support real-time vehicle-to-vehicle communication. *EURASIP Journal on Wireless Communications and Networking*, pages 1–13, 2009.

[30] Position Indicating System (US patent 5506587), 09 1996.

[31] R.A. Saeed, M.A. Abakar, A.A. Hassan, and O.O. Khalifa. Design and evaluation of lightweight IEEE802.11p-based TDMA MAC method for road side-to-vehicle communications. In *Computer and Communication Engineering (ICCCE), 2010 International Conference on*, pages 1–5, May 2010.

[32] ETSI TS 102 637-2: Intelligent Transport Systems (ITS); Vehicular Communications; Basic Set of Applications; Part 2: Specification of Co-operative Awareness Basic Service. Technical report, European Telecommunications Standards Institute (ETSI), 2010.

[33] ETSI TS 102 637-3: Intelligent Transport Systems (ITS); Vehicular Communications; Basic Set of Applications; Part 3: Specification of Decentralized Environmental Notification Basic Service. Technical report, European Telecommunications Standards Institute (ETSI), 2010.

[34] Xue Yang, Jie Liu, N.F. Vaidya, and Feng Zhao. A vehicle-to-vehicle communication protocol for cooperative collision warning. In *Mobile and Ubiquitous Systems: Networking and Services, 2004. MOBIQUITOUS 2004. The First Annual International Conference on*, pages 114–123, 2004.

[35] C. Khorakhun, H. Busche, and H. Rohling. Congestion control for VANETs based on power or rate adaptation. In *Proceedings of the 5th International Workshop on Intelligent Transportation (WIT)*, 2008.

[36] R. Baldessari, D. Scanferla, L. Le, W. Zhang, and A. Festag. Joining forces for VANETs: A combined transmit power and rate control algorithm. In *6th International Workshop on Intelligent Transportation (WIT)*, 2010.

[37] M. Torrent-Moreno, J. Mittag, P. Santi, and H. Hartenstein. Vehicle-to-Vehicle Communication: Fair Transmit Power Control for Safety-Critical Information. *Vehicular Technology, IEEE Transactions on*, 58(7):3684–3703, 2009.

[38] J. B. Kenney, G. Bansal, and C. E. Rohrs. LIMERIC: a linear message rate control algorithm for vehicular DSRC systems. In *Proceedings of the Eighth ACM international workshop on Vehicular inter-networking*, pages 21–30. ACM, 2011.

[39] T. Tielert, D. Jiang, Qi Chen, L. Delgrossi, and H. Hartenstein. Design methodology and evaluation of rate adaptation based congestion control for Vehicle Safety Communications. In *Vehicular Networking Conference (VNC), 2011 IEEE*, pages 116–123, 2011.

[40] A. Alonso, A. Paier, T. Zemen, N. Czink, and F. Tufvesson. Capacity Evaluation of Measured Vehicle-to-Vehicle Radio Channels at 5.2 GHz. In *Communications Workshops (ICC), 2010 IEEE International Conference on*, pages 1–5, 2010.

[41] A. Alonso, C. Mecklenbräuker, A. Paier, T. Zemen, N. Czink, and F. Tufvesson. Temporal evolution of channel capacity in vehicular MIMO channels in the 5 GHz band. In *Electromagnetic Theory (EMTS), 2010 URSI International Symposium on*, pages 938–941, 2010.

[42] V. Shivaldova, G. Maier, D. Smely, N. Czink, A. Alonso, A. Winkelbauer, A. Paier, and C.F. Mecklenbräuker. Performance evaluation of IEEE 802.11p infrastructure-to-vehicle tunnel measurements. In *Wireless Communications and Mobile Computing Conference (IWCMC), 2011 7th International*, pages 848–852, 2011.

[43] M. El Masri. IEEE 802.11e: The Problem of the Virtual Collision Management within EDCA. In *INFOCOM 2006. 25th IEEE International Conference on Computer Communications. Proceedings*, pages 1 –2, april 2006.

[44] Y. Jian and S. Chen. Can CSMA/CA networks be made fair? In *Proceedings of the 14th ACM International Conference on Mobile Computing and Networking*, pages 235–246. ACM, 2008.

[45] S. Subramanian, M. Werner, S. Liu, J. Jose, R. Lupoaie, and X. Wu. Congestion control for vehicular safety: synchronous and asynchronous MAC algorithms. In *Proceedings of the ninth ACM international workshop on Vehicular inter-networking, systems, and applications*, VANET '12, pages 63–72, New York, NY, USA, 2012. ACM.

[46] R. Kjellberg. Capacity and Throughput using a Self Organized Time Division Multiple Access VHF Data Link in Surveillance Applications. *Department of Computer and System Sciences*, page 53, 1998.

[47] N. An, T. Gaugel, and H. Hartenstein. VANET: Is 95% probability of packet reception safe? In *ITS Telecommunications (ITST), 2011 11th International Conference on*, pages 113–119, 2011.

[48] P. Rajmic and K. Molnar. Optimized Algorithm for Probabilistic Evaluation of Enhanced Distributed Coordination Access according to IEEE 802.11e. In *Telecommunications and Signal Processing TSP2010*, 2010.

[49] K. Bilstrup, E. Uhlemann, E. G. Ström, and U. Bilstrup. On the ability of the IEEE 802.11 p and STDMA to provide predictable channel access. In *Proceedings of the 16th World Congress on Intelligent Transport Systems (ITS)*, page 10, 2009.

[50] K.S. Bilstrup, E. Uhlemann, and E.G. Ström. Scalability Issues of the MAC Methods STDMA and CSMA of IEEE802.11p when used in VANETs. In *Communications Workshops (ICC), 2010 IEEE International Conference on*, pages 1–5, May 2010.

[51] Recomendations ITU-R M.1371-1, "Technical characteristics for universal shipborne automatic identification system uning time division multiple accress in the VHF maritime mobile band".

[52] The Mathworks - MATLAB and Simulink for Technical Computing http://www.mathworks.com/.

[53] SIMULINK - Simulation and Model-Based Design http://www.mathworks.com/products/simulink.

[54] Stateflow-Design and Simulate State Machines and Control Logic http://www.mathworks.com/products/stateflow.

[55] Network Simulator ns-2, http://www.isi.edu/nsnam/ns/.

[56] J. Ryu, J. Lee, Sung-Ju Lee, and T. Kwon. Revamping the IEEE 802.11a PHY simulation models. In *Proceedings of the 11th international symposium on Modeling, Analysis and Simulation of Wireless and Mobile Systems*, MSWiM '08, pages 28–36, New York, NY, USA, 2008. ACM.

[57] A. Kuntz, F. Schmidt-Eisenlohr, O. Graute, H. Hartenstein, and M. Zitterbart. Introducing probabilistic radio propagation models in OMNeT++ mobility framework and cross validation check with NS-2. In *SimuTools'08*, pages –1–1, 2008.

[58] J. Mittag, S. Papanastasiou, H. Hartenstein, and E.G. Strom. Enabling Accurate Cross-Layer PHY/MAC/NET Simulation Studies of Vehicular Communication Networks. *Proceedings of the IEEE*, PP(99):1 –16, 2011.

[59] V. Shivaldova, G. Maier, N. Smely, D. ; Czink, A. Paier, and C.F. Mecklenbrauker. Performance Analysis of Vehicle-to-Vehicle Tunnel Measurements at 5.9GHz. In *XXX URSI General Assembly and Scientific Symposium of International Union of Radio Science (URSI GASS 2011)*, July 2011.

[60] ROADSAFE Project, http://portal.ftw.at/projects/roadsafe, 2011.

[61] K. Sjöberg, E. Uhlemann, and E.G. Ström. Delay and Interference comparison of CSMA and self-organzing TDMA when used in VANETs. In *7th Int. Wireless Communications and Mobile Computing Conference (IWCMC)*, 5-8 July 2011.

[62] K. Sjöberg. Standardization of Wireless Vehicular Communications within IEEE and ETSI. In *IEEE VTS Workshop on Wireless Vehicular Communications, Halmstad University, November 2011.*

[63] Nakagami. *The m-distribution, a general formula of intensity distribution of the rapid fading*. Oxford, England, Pergamon, 1960.

[64] Lin Cheng, B.E. Henty, D.D. Stancil, Fan Bai, and P. Mudalige. Mobile Vehicle-to-Vehicle Narrow-Band Channel Measurement and Characterization of the 5.9 GHz Dedicated Short Range Communication (DSRC) Frequency Band. *Selected Areas in Communications, IEEE Journal on*, 25(8):1501 –1516, oct. 2007.

[65] ETSI TR 102 861: Intelligent Transport Systems (ITS); On the Recommended Parameter Settings for using STDMA for Cooperative ITS; Access Layer Part. Technical report, European Telecommunications Standards Institute (ETSI), 2011.

[66] S. Rappaport. *Wireless Communications - Principles and Practice*. Prentice-Hall, 1996.

[67] Standards I. E. E. E. Association. ANSI IEEE 802.3 Standard. Technical report, IEEE, May 1998.

[68] K. Sjoberg, E. Uhlemann, and E. G. Strom. How severe is the hidden terminal problem in VANETs when using CSMA and STDMA? In *Vehicular Technology Conference (VTC Fall), 2011 IEEE*, pages 1–5. IEEE, 2011.

[69] A. Taimoor. Measurement based Shadow Fading Model for Vehicle-to-Vehicle Network Simulations. *IEEE Transactions on Vehicular Technology: Special Section on Vehicular Network and Communication System, From Laboratory into Reality*, 2012.

[70] ETSI DTS 101 539-1: Draft v.0.0.6, Intelligent Transport Systems (ITS); V2X Applications; Part 1: Road Hazard Signalling (RHS), Application requirements specification. Technical report, European Telecommunications Standards Institute (ETSI), May 2012.