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Dependability of Decentralized Congestion Control for varying VANET density

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***Abstract*—IEEE 802.11p is an amendment to the IEEE 802.11 standard for Wireless Access in Vehicular Environments (WAVE). Lower layer wireless transmission formats and protocols are defined for both vehicle-to-infrastructure and vehicle-to-vehicle communication links to support cooperative Intelligent Transport Systems (ITS). The Medium Access Control (MAC) layer uses carrier sensing as a means for detecting the busy state of the radio channel before transmitting. In heavily loaded Vehicular Ad-hoc NETworks (VANETs) the channel access delay when attempting to access the channel increases unpredictably when it is sensed as busy. The European Telecommunications Standards Institute (ETSI) defines safety-related messages. These messages require a dependable behaviour of the communication link. In this context, dependable behaviour translates to the reliable delivery of data packets within a specified deadline regardless of changes in the traffic density. Unfortunately, the WAVE amendment does not fulfil the requirements for such dependable behaviour. This contribution reports on performance evaluations by simulation studies of the IEEE 802.11p MAC and the Decentralized Congestion Control (DCC) mechanism specified by ETSI in addition to the existing Enhanced Distributed Channel Access (EDCA). The simulation scenario under study is a two VANET merging highway situation. The MAC protocol has to adapt to variable traffic densities in this scenario. The performance is evaluated in terms of coverage range and MAC-to-MAC delay reliability, and DCC state stability. Furthermore, a novel performance indicator a defined, evaluated, and discussed which the authors have named data novelty. Finally, a multistate-active DCC mechanism is proposed, which achieves a dependable behaviour.**

I. Introduction

FUTURE cooperative traffic safety applications depend on the timely exchange of data among vehicles and the road infrastructure via wireless communications. These applications focus on improving road safety and aim to increase the drivers' and vehicles' information horizon beyond the line of sight. The vehicles use messages to monitor their surrounding traffic situation and to detect deviations from safe behaviour. The European Telecommunication Standards Institute (ETSI) has defined two types of messages for safety-related applications, namely Cooperative Awareness Messages (CAM) [1] and Decentralized Environmental Notification Messages (DENM) [2]. CAMs are broadcasted periodically, with an update rate of 1—10 Hz depending on the context. CAMs contain the position, speed, and heading of the vehicle, they are time-triggered and broadcasted continuously. The CAM payload size is 200 byte, to which some security overhead is added. DENMs, on the other hand, are event-driven and and triggered when a safety-critical situation occurs. The Wireless Access in Vehicular Environments (WAVE) standard which is adopted in the USA does not have a distinct name for event-driven type of messages, but time-triggered messages are called Basic Safety Messages (BSM). Both message types require predictability, whereas CAM/BSMs have modest reliability requirements and DENMs have high 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. Therefore 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. The IEEE 802.11p [3]uses Carrier Sense Multiple Access with Collision Avoidance (CSMA/CA) as Medium Access Control (MAC) with support for Quality of Service (QoS) through IEEE 802.11e (this is known as Enhanced Distributed Carrier Access, EDCA). In Europe a profile standard of IEEE 802.11p has been approved by ETSI which is called ITS-G5 [4]. As stated in [5], the two lowest layers of the ETSI TC ITS protocol stack are almost identical to the WAVE approach with the exception that WAVE has the MAC-sublayer extension 1609.4 while ITS-G5 requires Decentralized Congestion Control (DCC) [6].

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The results in [7] showed that for different Vehicular Ad-hoc NETwork (VANET) densities there is a certain stabilization time required for dependable CSMA/CA performance for safety-related communications. This contribution extends the results in [7] and reports on DCC performance in VANETs with a time-varying traffic density. This occurs whenever two VANETs merge. The aim is to evaluate the communication protocol performance in three different stages of a VANET merging scenario: initially, when the two VANETs are created, secondly, when they merge into a single VANET, and, finally, when they separate again. The questions that arise are: How does EDCA perform on varying VANET density situations? Does the DCC enhance the EDCA performance? Does the reliable performance hold throughout the whole simulation time? This contribution evaluates the performance of the IEEE 802.11p MAC and the DCC mechanism recently specified by ETSI. And it proposes multistate-active DCC mechanism that achieves a robust and reliable performance. 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.

The remainder of the paper is structured as follows. Section II summarizes the background and related work on the MAC layer for vehicular communications and congestion control mechanisms. Section III introduces the basics of EDCA and the DCC mechanism, specifying the goals and how they should be implemented. A set of performance indicators for communication protocol evaluation is defined in Sec. IV. Next, the protocol mechanisms are investigated by simulation studies in the scenarios described in Sec. V. The performance indicators for single nodes as well as the VANET are analyzed and discussed in Sec. VI. Finally our conclusions are summarized.

II. Background and Related Work

In the field of vehicular MAC layers, two distinct lines of development have been followed to overcome the limitations imposed by vehicular propagation channels in roadway environments. On the one hand these are collision avoidance medium access algorithms, where nodes adopt a handshaking approach prior to sending messages. Ref. [8] presents a secure MAC protocol for VANETs with different message priorities for various types of application, focusing more on improving security and data integrity rather than on time critical message delivery. In Ref. [9] a deeper study is carried out on the delays introduced by the IEEE 802.11p MAC layer protocol. The results show the delay dependency on load (in Mbps). On the other hand, there is an also alternative line of MAC development, based on time-slotted protocols adapted to the VANET environment. Refs. [10]–[16] stem from Slotted Aloha (S-Aloha) [17]. These time-slotted approaches suffer from two major drawbacks: (1) they cannot stably handle scalability in overloaded situations and (2) slot allocation as perceived by a particular node is not distributed among the neighbouring nodes. In 2009 the work of [18] considered Time Division Multiple Access (TDMA) as potential collision avoidance MAC method for vehicular environments. TDMA [19] 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 in every period. As vehicular networks are dynamic in space and time, the slot assignment must be validated the vehicular network evolves 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 shortcomings for time-slotted approaches. Subsequently in 2010, [20] proposed a different TDMA solution for infrastructure-to-vehicle communication. This approach is implemented in a novel sub-layer on top of the conventional IEEE 802.11p MAC. The solution is likely feasible for infrastructure-to-vehicle communication scenarios, but much less so in a vehicle-to-vehicle communication context, where the size of the coverage area is not as important as a the reliability of the packet transmission at low latency.

DCC is a cross-layer mechanism that varies the parameter setting of the PHY layer based on a reference measured in the MAC layer. Its aim is to provide a fair and harmonized channel access. This means limiting the load of a subset of users either by reducing the transmit power, packet generation rate, or varying some of the threshold values in the communications which affect the channel load. Although, the DCC mechanism is being amended at the access layer, it actually is a cross-layer approach. The side effects of data congestion are managed in the Access [6], Network [21] and Facilities layer [22]. It may be feasible to reduce the access layer mechanism and incorporate approaches proposed in [23] with the aim of counteracting the poor effectivity of current algorithms [24].

The contribution on DCC of [25] evaluates the DCC behaviour under various channel loads and their results show that the DCC technique is not very effective with the specified parameter settings. This contribution shares this point of view giving insights for performance improvements. Regarding solutions for improving individual sub-mechanisms, the most prominent proposal for handling scalability through Transmit Power Control (TPC) is found in [26]. 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, and then locally solves the so-called Congestion Control under Fairness constraints (CCF) problem, thirdly computed values are exchanged among the neighbours and finally a minimum transmit power is selected. The computed solution is sub-optimum in general because the carrier sense ranges are not symmetric and likely larger than the transmission range. Therefore, a multi-hop strategy is employed, which leads to considerable overhead in communication. Finally [23] 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 and the current aggregate rate is calculated. The proposed LInear MEssage Rate Integrated Control (LIMERIC) adapts these linearly. The idealized case uses the aggregate offered rate, which is practically very difficult to infer. In contrast, the Channel Busy Ratio (CBR) is easy to measure and to use in the controller. For the specification of a closed-loop controller, the current line of development in research is based on the PULSAR [27] information sharing protocol approach for LIMERIC by using distributed feedback. Due to latency constraints, the traffic safety data must be transmitted in a single hop, such that D-FPAV is not applicable and a joint TPC-TRC solution seems to be most suitable.

This contribution is complementary to recent work in 2014 on the vehicular MAC layer. For Vehicle-to-Infrastructure (V2I) communication, [28] proposes a new handover scheme for IEEE 802.11p . The new handover scheme mitigates issues caused by listening to the frame service announcement on the Control Channel (CCH) by anticipating the entire handover phase (i.e. before it starts). For Vehicle-to-Vehicle (V2V) communication, new analytical models have been proposed [29] which allow the calculation of the broadcast delay of each Access Category (AC). In the field of signal processing, successive interference cancellation has been implemented by [30]. Two MAC protocols' performance for V2V have been compared, Direct-Sequence CDMA and CSMA/OFDM, when both use a Successive Interference Canceller (SIC). A multiple channel switching mechanism has also been studied [31]. This proposes a multiple schedules based channel access method for enhancing channel utilization in VANET by adopting multiple channel switching. Finally, [32] presents the so-called Enhanced Priority VANET Scheme (EPVS) where the distance range between vehicles is estimated and the transmission priority level is categorized based on the reliable distance range and data type.

Our contribution here deepens the study of the reliable distance range in highway scenarios. The novel contributions are

1) a proposal for using multistate active DCC mechanisms for VANETs and
2) the evaluation of the corresponding performance of the DCC mechanism.

Further, it is shown that traffic scenarios with a time-variant traffic density pose severe challenges for reliable service provisioning for traffic safety applications.

III. MAC Layer for traffic safety communication

The IEEE 802.11p standard for vehicular communications inherits the EDCA medium access control mechanism. EDCA was originally devised for scheduling best-effort unicast data traffic. The goal was to avoid collisions regardless of the delay. The IEEE 802.11p channel access procedure of *a vehicle in unicast mode* starts by listening to the channel before transmission and if the channel activity is perceived idle for a predetermined listening period, the vehicle starts transmitting 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. The Contention Window (CW) is then set to the minimum CW size (CW_{min}). And a back-off value is randomly selected [0,CW]. The back-off counter is decremented every time the channel is sensed free for Arbitration Inter-Frame Spacing (AIFS) amount of time, until the back-off counter expires and the message is finally transmitted. Still the unicast transmission is not completed until an ACKnowledgement message (ACK) is successfully received at the transmitter. If the ACK is not successfully received, a maximum number of transmission attempts are defined for that message. If this maximum index is not reached and CW is not larger as CW_{max}, the 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 is achieved without receiving the ACK, the transmission is said to be failed and the message is dropped. The channel access procedure of *a vehicle in broadcast mode* waits for no ACK. It also starts by listening to the channel before transmitting and if the channel activity is perceived as idle for an AIFS period, the vehicle can start transmitting 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 CW size (CW_{min}). And a back-off value is randomly drawn [0,CW]. The back-off counter is decremented every time the channel is sensed idle for AIFS amount of 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 both 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 aforementioned, 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, which lead to a dangerous situation. Other than those MAC layer drops, there are also PHY layer drops due to the nature of the communication channel. These happen because vehicles do not have full connectivity to all other neighbours. Thus transmissions can start simultaneously because of hidden terminals (by obstacles or distance).

In the case of traffic safety-related data, the main requirement on the delay is to keep it low and predictable, as these messages are most valuable the sooner they are scheduled. This also avoids MAC drops. Regarding the coverage range, safety-related messages are one-hop, therefore is important that they are disseminated as far as possible from the transmitter, so that distant neighbours can react on time. IEEE 802.11p 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. Hence, the QoS restrictions related to traffic safety-related applications cannot be fulfilled and the overall VANET performance is unreliable. The work in [7] shows that for different VANET densities there is a certain stabilisation time required so that the IEEE 802.11p MAC performs reliably in terms of meeting a certain MAC-to-MAC delay for safety-related communications (i.e. at least the 90% of the generated messages in the VANET have to be delivered on-time, according to an automotive industry partner advice).

In the field of medium access control, the authors define dependability as a measure of a systems availability (i.e. readiness for correct service) and reliability (i.e. continuity for correct service). The main drawback of the IEEE 802.11p MAC is the poor performance when the channel is heavily loaded. The carrier sensing procedure before sending is translated into too long waiting times for the safety message to fulfill its warning purpose. 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 alternative to be inherited by the IEEE 802.11p standard 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.

ETSI has proposed a *decentralized congestion control* scheme in order to mitigate the IEEE 802.11p MAC layer congestion issues at high vehicle densities [6]. The DCC mechanism [33] is based on an underlying state machine where the transmit parameters are chosen, based on the observed Channel Load (CL). It does not require changes in the existing PHY/MAC specification.

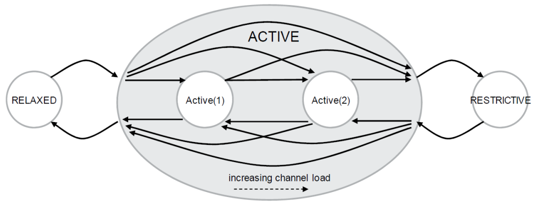

Fig. 1. Currently proposed DCC Mechanism: The state machine proposed by ETSI DCC framework [6]

The main goal of the DCC is to ease the channel load, so that safety data traffic can be served on time. It is a cross-layer solution because based on channel state information (acquired using channel probing) PHY layer parameters are set in order to enhance the IEEE 802.11p MAC performance. DCC consists of the following mechanisms:

- TPC: controls the average transmit power per packet.
- Packet Interval (PI) (aka. TRC): varies the node transmission duty cycle, i.e. the fraction of time during which a node transmits.
- Transmit Data-rate Control (TDC): determines the data rate used by the node to transmit its packets.
- CST (aka. DCC Sensitivity Control): adapts the clear channel assessment to resolve the local channel congestion.
- Transmit Access Control: introduces a transmit queuing concept to handle packet priority

There have been several studies presented in the previous section that have investigated the individual effectiveness of some of the mechanisms for mitigating traffic congestion and if they are stable. In this contribution the transmission parameters associated with a certain state include transmit power (P), packet transmission interval (PI), carrier sense threshold (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 authors will implement TPC, TRC and CST parametrisation.

IV. Performance Indicators

The most widely used metric to benchmark MAC performance is the *aggregate throughput* $\mathcal{T}$. This quantifies the successfully delivered data per unit time interval and is useful in settings where the data rate or message size are variable. Here,

$$\mathcal{T} = N \cdot P \cdot t, \tag{1}$$

where N denotes the number of bits per packet, P is the number of packets per frame, and t is the frame duration in seconds. In the case of safety-related data services it is of rather limited use.

The *Probability of packet reception (PPR)* [34] provides a metric for the dissemination of an individual data transmission. Requirements can be set by specifying a minimum *PPR* as a threshold PPR_{th}, i.e. $PPR > PPR_{th}$). The *PPR* does not provide a global view of the QoS.

The *Cumulative Distribution Function of the MAC-to-MAC delay (CDF)* in [5] is a suitable reliability indicator in terms of the packet delivery delay.

$$F_{\tau_{MM}}(\tau_{dl}) = P(\tau_{MM} \leq \tau_{dl}) \tag{2}$$

This metric does, however, not provide a reliability indicator in terms of coverage range which is a crucial aspect of information dissemination.

To this aim, the *Complementary Cumulative Distribution Function of coverage ranges (CCDF)* is defined in Sec. IV-A. To our knowledge, this is the missing piece of the tuple $(\Delta t, \Delta d)$ to fully define the performance of a safety-related messaging, in terms of meeting a MAC-to-MAC delay (Δt) and covering dissemination range (Δd). Additionally, Sec. IV-B defines a performance indicator for evaluating TRC performance, i.e. data novelty.

A. Complementary Cumulative Distribution Function of Coverage Ranges in time

In a VANET of R vehicles, the nth transmitter $(1 \leq n \leq R)$ broadcasts its priority message from location $\vec{x}_n(t)$. For each of the n transmissions 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 *PPR* of the transmitted package according to the used channel model is calculated. Losses and drops are taken into account by specifying a PPR threshold.

Then the coverage range is calculated for the transmissions that are deadline compliant. Coverage range for one transmission at time t is defined as,

$$\delta_t = \max_{1 \leq r \leq R} |\vec{x}_n(t) - \vec{y}_r(t+\tau)| \ , \tag{3}$$

where the *PPR* is set for a deadline on the MAC-to-MAC delay $\tau < \tau_{\max}$ defined depending on the traffic priority class.

A set of distances is defined for each transmitter per channel realisation, i.e.,

Let D be the set of coverage ranges of the correctly decoded CAM messages, e.g. for CAM No. 1, 5, 20, $\ldots$, n then

$$D = \{\delta_1, \delta_5, \delta_{20}, \ldots, \delta_n\} \, . \tag{4}$$

By evaluating the CCDF of D, the probability of coverage range versus distance to the transmitter is obtained for a given QoS per frame realisation. This QoS is determined by the specified *PPR* threshold and a given delivery 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.

For each broadcasted message by an individual vehicle (node under study) the maximum transmitter-receiver distance is defined as the coverage range. The CCDF of coverage range defines the probability of reaching a furthest away distance achieved by a broadcasted message per channel realisation (frame). It provides a reliability indication in terms of dissemination range.

B. Data novelty of the Safety Information present in the VANET

This performance indicator is defined for evaluating the performance of TRC algorithms. It quantifies the data novelty in terms of the *age* of the messages. The age is the validity time since it is generated at the transmitter until it is discarded at the receiver. For safety-critical data it is of primary importance that the broadcasted data is as contemporary as possible, i.e. the transmissions are most up-to-date. This parameter is calculated as the arithmetic mean of the age of all the messages present in the network over time,

$$\overline{T}_{\text{age}}(t) = \frac{T_1(t) + T_2(t) + \ldots + T_n(t)}{n} \ . \tag{5}$$

V. Simulation Scenario

Using the IEEE 802.11p MAC scheme, every node senses its neighbors which transmit a signal above

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its carrier sensing threshold level. What will follow when a VANET cluster A traveling in one direction meets another VANET cluster B and they merge? This is a common situation in cases such as multi-level highway entries to large cities or multiple lane highways during rush hours. Cluster A is unsaturated and well-organized internally, i.e., all nodes transmit their messages without interfering with each other. Next, cluster B turns up, also well-organized internally. How long will it take before clusters A and B have re-organized, and a new *common* perception of the channel state is achieved? This contribution aims to evaluate the performance of different DCC mechanisms in a VANET in transient state (time-variant traffic density) and compare it with plain EDCA. CAM/BSM traffic is assigned to a medium priority class whereas DENMs are assigned the highest priorities.

Ref. [7] showed that when using CSMA/CA (highest priority parameters) in high traffic density situations the probability of MAC-to-MAC delay drops to 80% for a specified 100 ms deadline, whereas the corresponding probability for the alternative MAC protocol SoTDMA decreases to 85%. These results are relevant during the start-up phase of a VANET where numerous channel access attempts take place within the same frame. By including EDCA and setting the data traffic priority characteristics to lower priority, SoTDMA results are achieved (as channel access attempts are more evenly distributed throughout the frame).

A three-state DCC mechanism based on absolute maximum ratings has been proposed and several questions arise which relate to the performance of the aforementioned mechanism: Do vehicles in different states have similar performance? Does this three-state machine perform well enough to provide a reliable service? How does the DCC mechanism adapt to a variable traffic density scenario? Does it provide dependability?

In order to compare and contrast the performance of both MAC schemes, IEEE 802.11p 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 by the authors. 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 [7], 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 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 scenario simulated is a six lane highway scenario where 400 vehicles (80% channel load) are traveling in opposite directions (see Fig. 2). The chosen scenario is a multi-lane highway, inherited from the work [18], since this is believed to be one of the most demanding scenarios for the MAC method. The high dynamics of the network imply that the high relative speeds (up to 300 km/h) will cause vehicles to rapidly move in and out of radio range of each other. The speed of each vehicle is modeled as a Gaussian random variable with different mean values for each lane, 23m/s (83 km/h), 30 m/s (108 km/h), and 37 m/s (133 km/h), and a standard deviation of 1m/s. The different speeds are chosen with the speed regulations of Sweden in mind. In this simulation 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 mobility simulation, there are three parameters to be set per new vehicle added to the VANET: *initialization time*, *lane* and *speed*. All the vehicles broadcast messages with a fixed data rate of 6 Mbps. The data traffic model is set up following the ETSI recommendations redefined in [35] for safety-related messages (broadcasted messages are 400 bytes long including all protocol overhead).

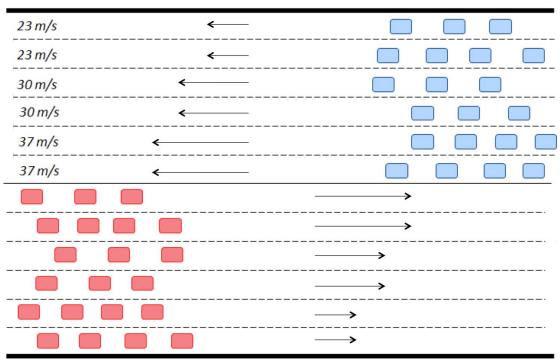

Fig. 2. Scenario description of two VANETs merging use case.

The used physical model, is a channel model suitable for such highway scenarios. The Nakagami m model [36] has previously been identified as a suitable probabilistic channel model for the VANET setting ([37]). The small-scale fading and large-scale fading are both represented by the Nakagami m model. The Probability Density Function (PDF) for the Nakagami

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m distribution is

$$f(x;m,P_r(d)) = \begin{cases} \frac{2m^m x^{2m-1}}{[P_r(d)]^m \Gamma(m)} e^{-\frac{mx^2}{P_r(d)}}, & \text{for } x > 0, \\ 0, & \text{else.} \end{cases} \quad (6)$$

where $m > 0.5$ represents the fading intensity, $P_r(d)$ denotes the average received power at distance *d*, and $\Gamma(\cdot)$ is the gamma function. Rayleigh fading statistics (without line-of-sight) are included by setting $m = 1$. Higher values of *m* can be used for approximating Rician distributed channel conditions where a line-of-sight path exists, whereas $m < 1$ models fading conditions that are considered to be more severe than Rayleigh fading. The m is distance-dependent and summarized in Tab. I.

TABLE I
DISTANCE-DEPENDANT *m*-VALUES IN THE NAKAGAMI MODEL [35]

Distance bin in meters	*m*
0 — 50	3.0
50 — 150	1.5
> 150	1.0

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

$$P_{r,\mathrm{dB}} = \begin{cases} 0, & \text{if } d \le d_0, \\ P_{r,dB}(d_0) - 10\gamma_1 log_{10}\frac{d}{d_0}, & \text{if } d_0 \le d \le d_c, \\ P_{r,dB}(d_0) - 10\gamma_2 log_{10}\frac{d}{d_c} & \\ -10\gamma_1 log_{10}\frac{d_c}{d_0}, & \text{if } d > d_c. \end{cases} \quad (7)$$

where numerical values are presented in Tab. II. 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.

TABLE II
THE PATH GAIN MODEL'S PARAMETERS [35]

Parameter	Value
Path gain γ_1	1.9
Path gain γ_2	3.6
Cut off distance d_c [m]	177
Reference distance d_0 [m]	10
Wave length λ [m]	0.0508

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

$$P_{r,\mathrm{dB}}(d_0) = P_{t,dB} - 10\log_{10}\left(\frac{\lambda^2}{(4\pi d_0)^2}\right), \quad (8)$$

where $d_0 = 10$ m and the wavelength, λ, is based on a carrier frequency of $f = 5.9$ GHz. The resulting Signal-to-Interference-plus-Noise Ratio (SINR) at the receiver is calculated using the formula in [38]. The noise power is set to -99 dBm and the SINR threshold is set to 6 dB.

Cut-off distance d_c is calculated as in [39], from the first Fresnel Zone with first ground reflection,

$$d_c = d_b + \frac{\lambda}{4} = \frac{4h_T h_R - \frac{\lambda^2}{4}}{\lambda} + \frac{\lambda}{4}, \quad (9)$$

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.

Regarding the parameter setting for the IEEE 802.11p MAC algorithm will be different depending on the data traffic priority. EDCA defines four different priority queues or Access Categories (ACs), each with different values of arbitrary interframe space and back-off range: AC Voice (AC_{VO}), AC Video (AC_{VI}), AC Best Effort (AC_{BE}) and AC Background (AC_{BA}). As concluded in [40], 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,

$$AIFS(AC) = AIFSN(N) \cdot aSlotTime + aSIFSTime, \quad (10)$$

where aSIFSTime stands for short interframe period, a small time interval between the frame and the acknowledgment. For the IEEE 802.11p 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. For this contribution AC_{VO} and AC_{VI} will be highest and medium priority, respectively. Clear Channel Assessment (CCA) threshold is set to -96 dB.

Fig. 3 shows simulation results of an individual node during the merging of two VANETs. In the top subfigure (Fig. 3a) the dynamic evolution of the simulated scenario is depicted. The situation displayed is the merging situation in the time instant t=100 s. The dot represents the placement on the road in time of the vehicle (node under study), when the rest of the performance indicators are evaluated.The performance indicators under study are:

- *Awareness and Emergency Coverage Range vs Time*: Depicted in Fig. 3b, it shows the maximum transmitter-receiver distance (i.e. maximum dissemination distance) vs time for two different QoS defined by probability of packet

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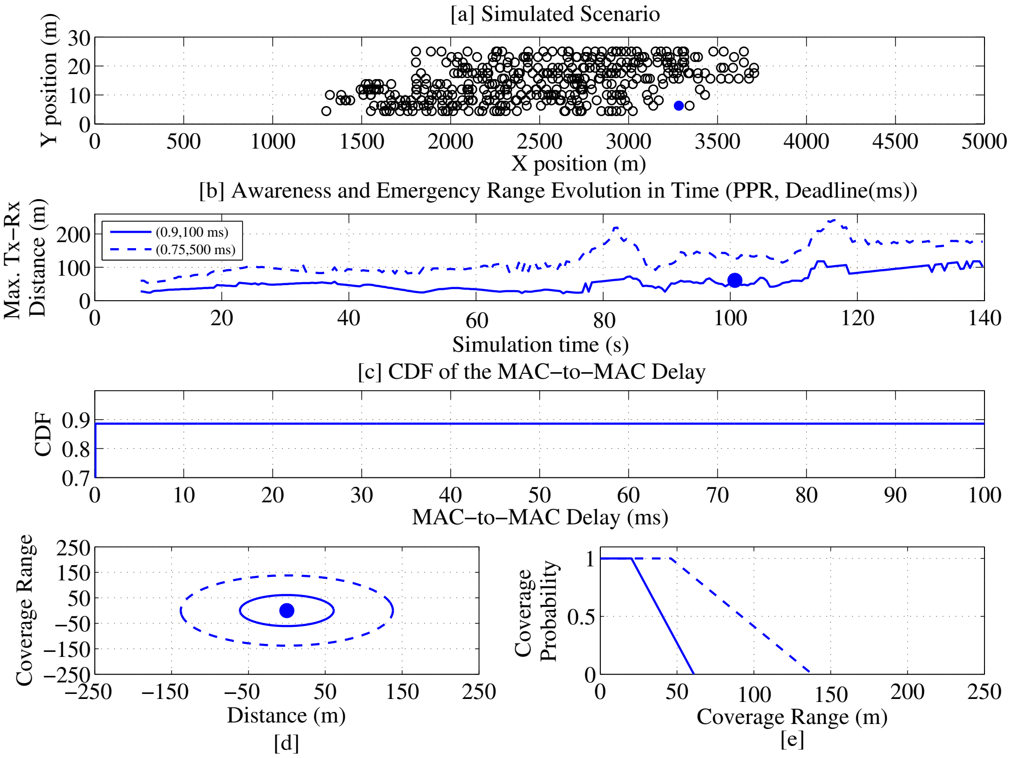

Fig. 3. Simulation Results for a Vehicle in Restrictive State

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.

- Empirical *Cumulative Distribution Function of the MAC-to-MAC Delay vs MAC-to-MAC Delay*: It depicts the percentage of the generated packets that ace a lower or equal MAC-to-MAC delay than a predefined threshold (see Fig. 3c). Sticking to the aforementioned QoS restriction, the significant CDF level to be analyzed is the related to 100 ms deadline.
- *Coverage Probability vs Coverage Range*: It reveals the different reliability regions for each channel realisation, based on the percentage of generated packets that were successfully received at different distances from the source (see Fig. 3d). In the case of using 500 ms packet interval, two packets are sent per frame, therefore the *coverage probability* has two levels/regions. For variable packet interval *coverage probability* is multilevel.
- *Coverage Range Evolution*: Is a dissemination reliability indicator shown in Fig. 3e. It defines the furthest away distance reached by a broadcast per channel realization (frame). The dot represents the node under study.

For the overall system performance (i.e. VANET 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.

VI. Results

In this section the performance of three different DCC mechanisms is evaluated in a transient VANET scenario. The first goal is to evaluate the enhancement introduced by this mechanism to the EDCA performance and the final goal is to design a suitable option that provides a dependable performance throughout the whole simulation time, also under strong traffic density variations. ETSI presented in [6] a three-state solution, where the cross-layer approach sets the PHY layer parameters packet interval, modulation and coding schemes, transmit power and carrier sensing threshold depending on the MAC layer parameter, channel load. A contribution of this work is the temporary analysis of the performance of individual nodes that joined the VANET in different instants of time. As mentioned before, vehicles join the road and depending on the channel load they set up the

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transmission parameters accordingly. Three different nodes are chosen so that the consistency of the DCC mechanisms is tested: a vehicle initialised in relaxed state, i.e. that entered the highway when $CL < 0.4$, a vehicle initialised in active state, i.e. that entered the highway when $CL \geq 0.4$ and a vehicle initialised in restrictive state, i.e. that entered the highway when $CL \geq 0.5$. Nodes that have joined the network with different load, go through different DCC states and is important to test the reliability of the solution for all possible iterations of the mechanism. Another important contribution is the study of the temporal evolution of the reliability performance of the whole VANET. This leads to identify possible network effects or reliability gaps due to inappropriate parameter settings or design of the DCC mechanism.

A. Performance of the Three-State DCC mechanism: highway scenario with Transmit Power Control

In this work a simplified version of the aforementioned three-state state machine is implemented. The values used in Fig. 4 are the limits given as absolute maximum allowed parameter range and not the values intended to be used as state parameters.

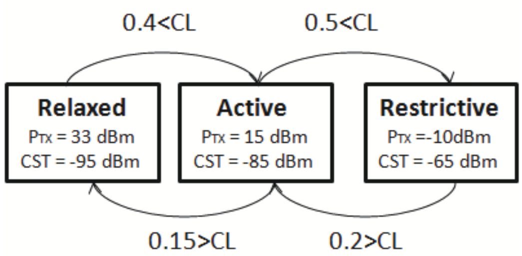

Fig. 4. Three-State Maximum Values DCC Mechanism design

The 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 three 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). In this scenario CAM/BSMs and DENMs have got a fixed PI (500 ms) 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) in order to enhance the performance of the maximum values DCC mechanism.

1) Individual Node Performance: The work [41] studied the impact of the priority of the data traffic and the emergency range evolution (for a QoS

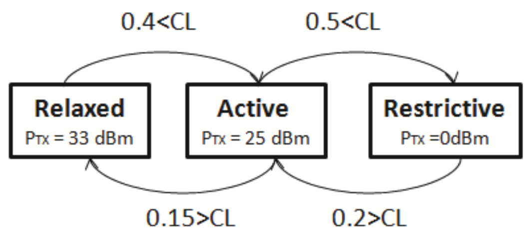

Fig. 5. Three-State Our DCC Mechanism design for CST=−90 dBm

(0.9,100 ms)) in time for highest (AC_{VO}) and medium (AC_{VI}) priority. The author corroborates for this specific DCC design that the medium priority data traffic is the most suitable traffic profile for CAM/BSMs in such heavily-loaded traffic scenarios. Therefore in further analysis only medium (AC_{VI}) priority data traffic results are going to be presented.

As mentioned in Sec. IV it is necessary to evaluate the dissemination of the information for a certain deadline. Is good to analyze both parameters (i.e. coverage range and MAC-to-MAC reliability) 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 three nodes initialized in different states of the DCC mechanisms.

a) Before merging: Fig. 6 shows the output of the simulation results at $t = 60\ s$. The top subfigure (Fig. 6a) shows the simulation scenario where the outlined blue node is the evaluated vehicle initialized in *relaxed state* (i.e. a vehicle that joined the network when $CL < 0.4$). This figure is very important to be aware of the time instant and the VANET scenario in which performance is evaluated. Author's three-state DCC proposal outperforms the rest in terms of coverage range (Δd) (see Fig. 6c and Fig. 6d) 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 $\geq 90\%$), as shown in Fig. 6b.

TABLE III
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	(0.9, 82 m)
Max Values Three-State DCC	(0.92, 56 m)

For a vehicle initialized in *active state* results in Tab. IV show 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

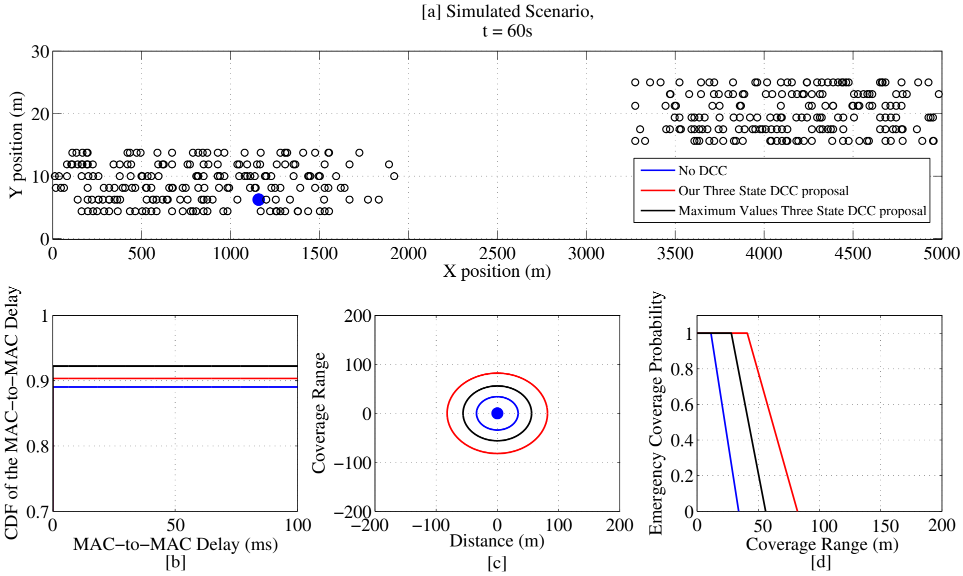

Fig. 6. Simulation Results for a Vehicle initialized in *Relaxed State* (t=60 s)

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. III), 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 IV
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	(0.98, 77 m)
Max Values Three-State DCC	(0.92, 65 m)

It is in the case of a vehicle initialized in *restrictive state*, Fig. 7, where the proposed three-state DCC mechanism draws a better performance in coverage range, Δd (see Fig. 7c), at the cost of losing reliability, CDF(Δt) (see Fig. 7b).

TABLE V
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	(0.85, 40 m)
Max Values Three-State DCC	(0.92, 20 m)

Comparing these 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 level above the reliability threshold.

Three different vehicle performances are evaluated in order to analyse different iterations of the DCC mechanism. The results in this scenario are the reference values for three sample vehicles (that entered the network when $CL < 0.4$, $CL \geq 0.4$ and $CL \geq 0.5$, respectively) when there is no traffic congestion (i.e. all the nodes are in relaxed state at $t = 60$ s).

b) Merging: During the merging situation (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 (see Fig. 8b). The vehicle is in active state for both DCC schemes. The three-state DCC proposal improves the coverage range of the maximum values three-state DCC mechanism in 10 m and the ones of the No DCC in 36 m. These results are depicted in Fig. 8.

TABLE VI
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	(0.92, 97 m)
Max Values Three-State DCC	(0.92, 87 m)

The results for a vehicle initialized in an *active state* node are equatable to the ones shown in Tab. VI.

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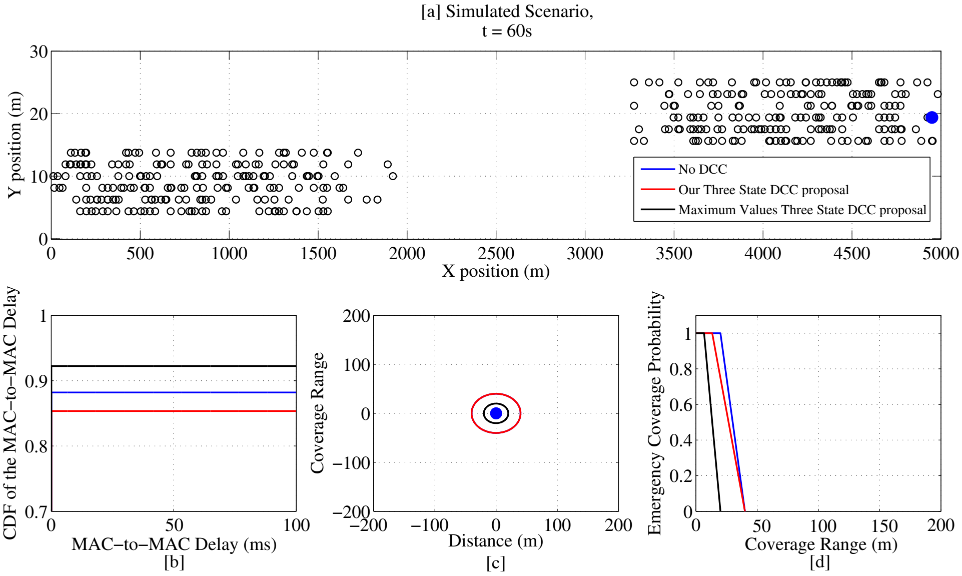

Fig. 7. Simulation Results for a Vehicle initialized in *Restrictive State* ($t = 60s$)

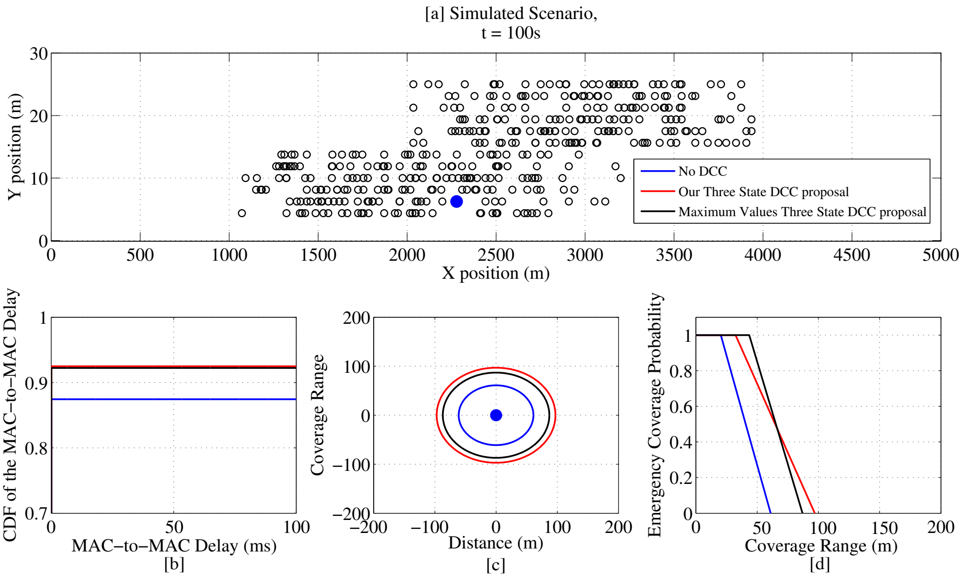

Fig. 8. Simulation Results for a Vehicle initialized in *Relaxed State* (t=100 s)

This is because in this time instant both scenarios are similar for both vehicles.

The problem arises once again with the performance of a vehicle initialized in *restrictive state*. Tab. VII shows the results where the vehicle is transmitting in active state using the author's DCC and in restrictive state using maximum value DCC. A more conservative parameter setting selection leads to a reliable performance. But it clearly points out that the DCC mechanism should be tuned properly, as 14 m coverage is too narrow for disseminating traffic safety-related information.

TABLE VII
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	(0.83, 72 m)
Max Values Three-State DCC	(0.92, 14 m)

c) After merging: After merging, different vehicles also have different performances in terms if coverage range depending on the state they are in. The vehicle initialized in *relaxed state* transmits in

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active state for both DCC schemes.

TABLE VIII
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	(0.88, 140 m)
Max Values Three-State DCC	(0.92, 83 m)

For a vehicle initialized in *relaxed state* only maximum values three-state DCC reaches a reliable performance (Fig. 9b) at the cost of losing coverage range (Fig. 9c and Fig. 9d). Whereas for a vehicle initialized in *active state* both DCC mechanisms achieve a reliable performance and enhance also Δd.

TABLE IX
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	(0.98, 121 m)
Max Values Three-State DCC	(0.92, 118 m)

Lastly, the recurrent problem for a vehicle initialized in *restrictive state* (shown in Tab. V, Tab. VII, Tab. XI) reappears and generates the following question: Is the amount of vehicles initialized in *restrictive state* important enough to impoverish significantly the overall system performance? This question leads to the next performance analysis, namely the VANET performance.

First the percentage of vehicles in each state is evaluated for the three different traffic situations (i.e. before, during and after merging). The table shown the transitions of the vehicles from one DCC state to the other at different simulation times. Due to the fact that both DCC designs share the same transition rules and CST values, similar results are applicable for both.

TABLE X
PERCENTAGE OF VEHICLES IN DIFFERENT DCC STATES DURING AT THEE DIFFERENT TIMES

	Relaxed	Active	Restrictive
Before (t=60 s)	100%		
Merging (t=100 s)	41%	25%	34%
After (t=140 s)		59%	41%

2) VANET Performance: The final analysis to make is the time evolution of the whole system performance. Fig. 10 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 to $'1'$ if the CDF(Δt) is above 90% and to $'0'$ if it falls below the threshold.

TABLE XI
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	(0.83, 96 m)
Max Values Three-State DCC	(0.92, 31 m)

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 network effect, i.e. reliability gap, until it stabilized ($91-127$ s) for 400 vehicles. This gap relates to the performance indicator stabilization time, $t_{stab}=36$ s. When separating both VANETs, the transient effect reappears. This is related to an increment of vehicles that enter the restrictive state (see Tab. X) and generate this network effect.

In conclusion, the three-state DCC mechanism increases reliability for high vehicle densities but dependability is not reached for variable traffic densities. The TRC proposed by ETSI at [6] shows the same VANET behaviour. For that purpose either multistate designs or other physical layer parameter settings (e.g. more complex transmit rate control algorithms) should be tried out.

B. Performance of the Multistate Active DCC mechanism: highway scenario with TPC and Transmit Rate Control

The next action to go for is to design such a DCC mechanism, which achieves a dependable performance, i.e. makes the aforementioned transient state shown in the reliability indicator graph in Fig. 10 disappear. Therefore the author has redesigned 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.

On top of that, 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 [42]. 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:

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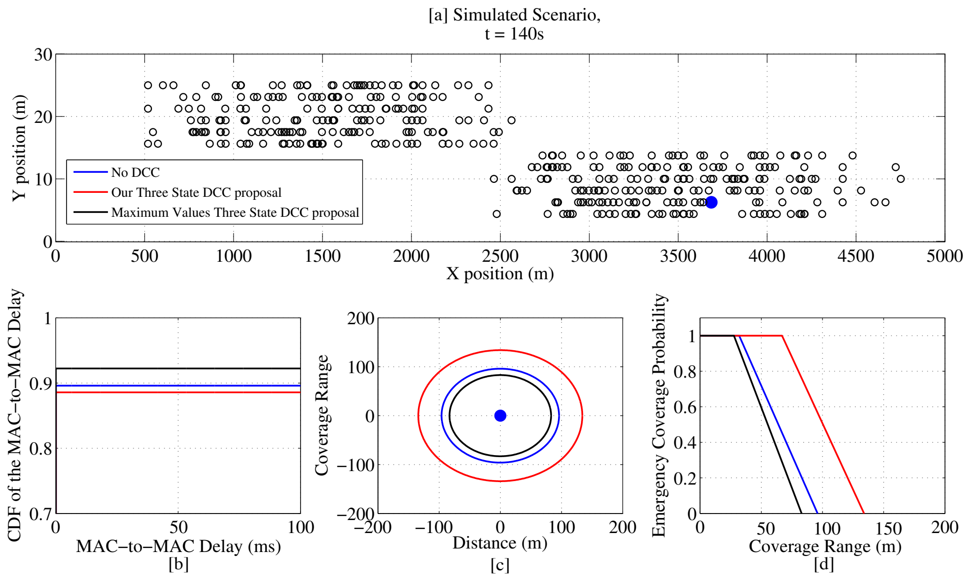

Fig. 9. Simulation Results for a Vehicle in initialized in *Relaxed State*(t=140 s)

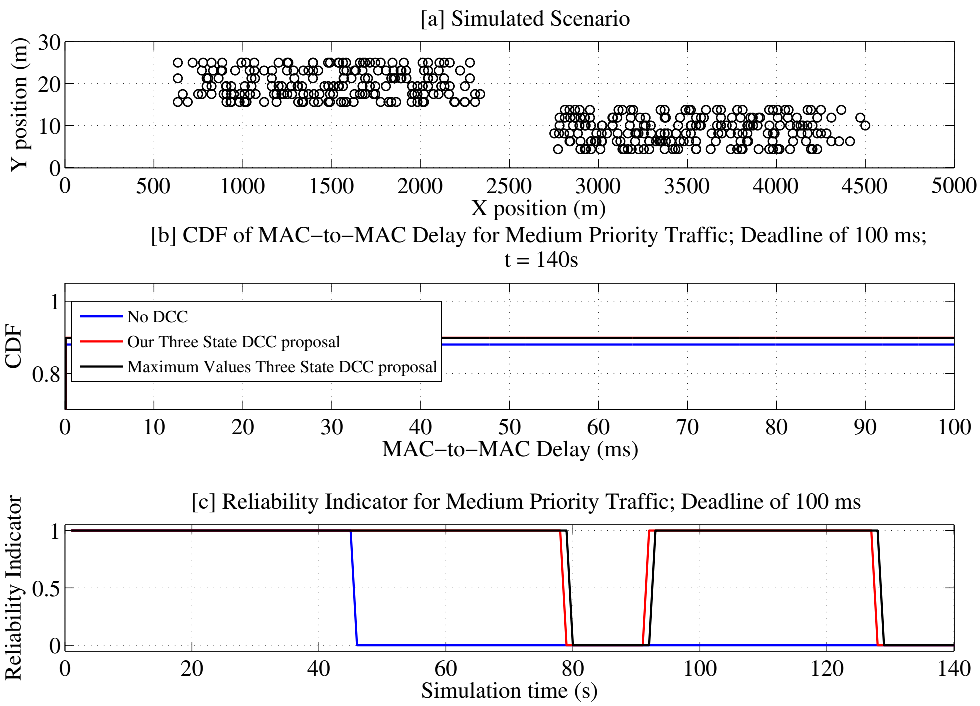

Fig. 10. System Performance for two VANET merging scenario: CDF of MAC-to-MAC Delay and Reliability

- 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 authors propose to change the CAM generation rate also when the channel load increases. As the channel load grows if 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 (see Fig.10c) and generates reliability gaps. Adapting this rate according to the channel load leads to lower channel access delays and hence lower MAC-to-MAC delays (τ_{MM}) suffered by the broadcasted safety information.

Author's next approach is a multistate active DCC mechanism implementing TPC and TRC. The TPC is driven by the measured channel load (CL). Using the aforementioned physical layer model, 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 [4] for dense traffic ($15 \leq \rho \leq 25$ vehicles/km). Same channel loads are grouped in different states. Finally the groups are assigned a transmit power and also different channel load values are selected as state transitions. The upwards transitions are calculated as $CL_{UP} = \frac{t(P_{RCVD})>CST)}{1\ s}$ and the downwards transitions are calculated as $CL_{DOWN} = \frac{t(P_{RCVD})>CST)}{5\ s}$. 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.

There are two ways to go for designing a suitable multistate active DCC mechanism: either (1) to make fine-coarse TPC state granularity, i.e. define more steps for the transmit power levels or (2) to make the whole design more robust against vehicle traffic density variation. Both attempts have benefits and drawbacks. The first solution it is a more accurate design, but this sensitivity also might lead to neighbour vehicles be in different states which turns into interferences and 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 scenario. The key goal at this point is to adapt the sensitivity so that the reliable performance is not lost during traffic density variations.

This contribution presents two solutions for those two options respectively: a more granular solution designed for $CST = -90\ dBm$ and another design selecting a more conservative value 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.

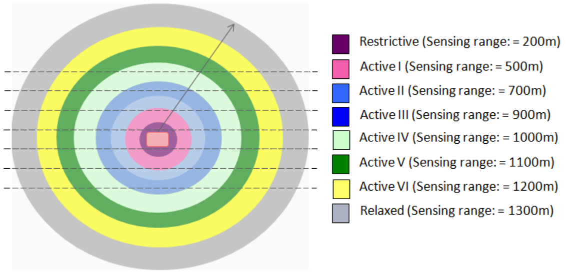

Fig. 11. TPC design for CST=−90 dBm

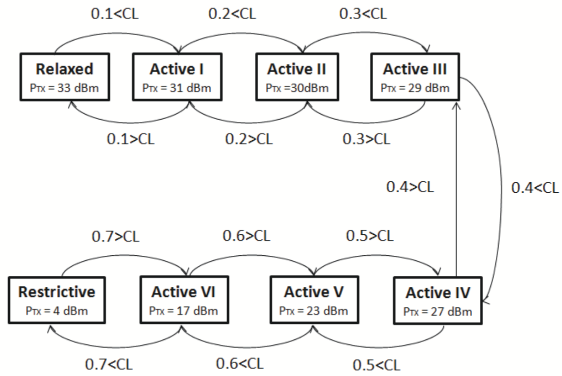

Fig. 12. Multistate active DCC Mechanism design for $CST = -90\ dBm$

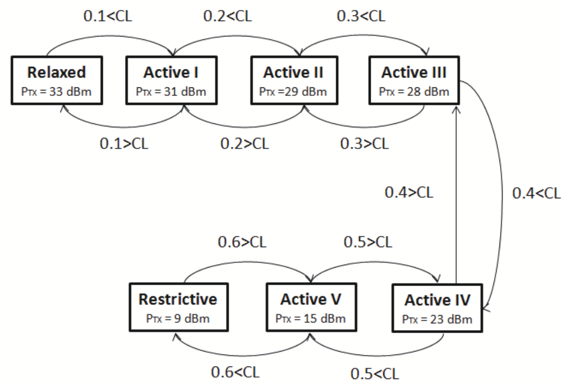

Fig. 13. Multistate active DCC Mechanism design for CST=−85 dBm

The procedure to study the results is parallel to the one described in Section VI-A, where first an individual node performance study is carried out and then the overall system performance.

1) Individual Node Performance:

a) Before merging: Fig. 14 displays the results for a vehicle initialized in *relaxed state* at t=60 s. It shows how the current DCC outperforms the No

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DCC and the multistate active DCC using $CST = -90\ dBm$. It reaches a reliable performance (see Fig. 14b) without sacrificing much coverage (see Fig. 14c and Fig. 14d) in comparison to the other multistate design (Tab. XII). Comparing the results to the ones achieved by author's three-state DCC collected in Tab. III, 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.

TABLE XII
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 DCC $CST = -90\ dBm$	(0.7, 59 m)
Multistate DCC $CST = -85\ dBm$	(0.93, 58 m)

The performance of a vehicle initialized in *active state*, displays 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. IV, 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 XIII
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 DCC $CST = -90\ dBm$	(0.97, 63 m)
Multistate DCC $CST = -85\ dBm$	(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 (see Fig. 15b) and coverage range (see Fig. 15c and Fig. 15d) are enhanced. Tab. XIV underlines up to 0.07 and 12 m enhancement, CDF(Δt) and Δd respectively.

b) 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. 16. Just the current multitstate approach reaches a reliable performance and and Tab. XV illustrates how in comparison to the multistate active DCC proposal using

TABLE XIV
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 DCC $CST = -90\ dBm$	(0.87, 61 m)
Multistate DCC $CST = -85\ dBm$	(0.95, 52 m)

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. VI, 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*).

TABLE XV
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 DCC $CST = -90\ dBm$	(0.83, 80 m)
Multistate DCC $CST = -85\ dBm$	(0.9, 66 m)

The results in Tab. XVI, related to a vehicle initialized in *active state*, displays similar results to the ones in Tab. XV. In comparison to the results in section VI-A, 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 XVI
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 DCC $CST = -90\ dBm$	(0.81, 86 m)
Multistate DCC $CST = -85\ dBm$	(0.91, 67 m)

The last use case is the performance of a vehicle initialized in *restrictive state*. 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. XVII).

c) After merging: And lastly in the after merging use case, the current multistate active DCC design

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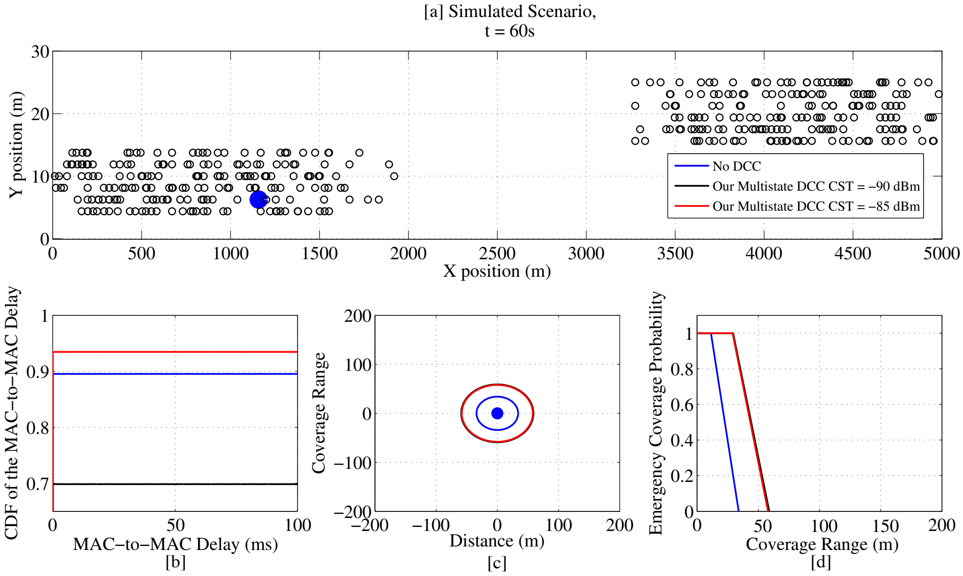

Fig. 14. Simulation Results for a Vehicle initialized in *Relaxed State* ($t = 60\ s$) for CST−85 dBm

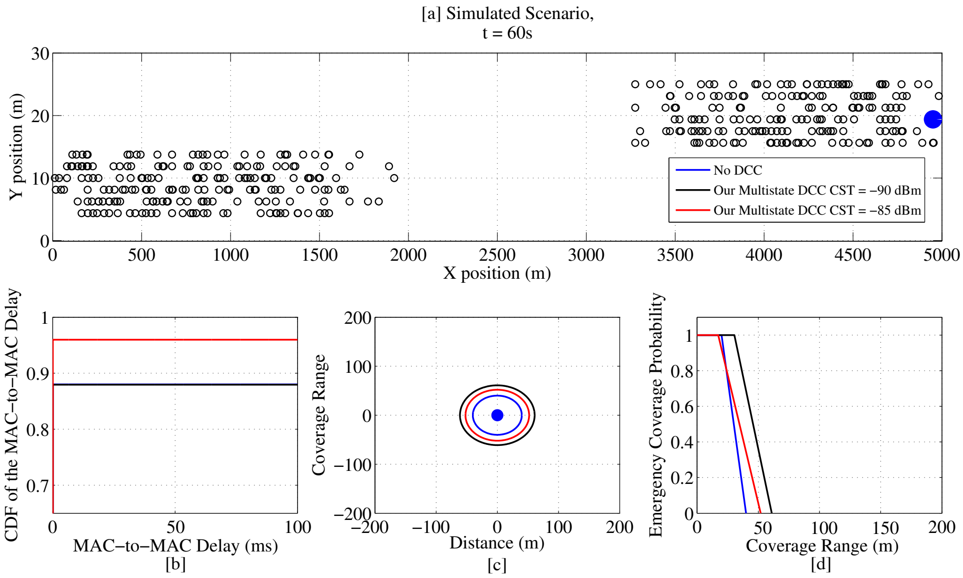

Fig. 15. Simulation Results for a Vehicle initialized in *Restrictive State* (t=60 s) for CST−85 dBm

TABLE XVII
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 DCC $CST = -90\ dBm$	(0.85, 127 m)
Multistate DCC $CST = -85\ dBm$	(0.93, 72 m)

TABLE XVIII
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 DCC $CST = -90\ dBm$	(0.94, 56 m)
Multistate DCC $CST = -85\ dBm$	(0.98, 102 m)

masters the rest of the performance for all the three studied profiles (a vehicle initialized in *relaxed, active and restrictive state*).

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. XVIII). On the other hand,

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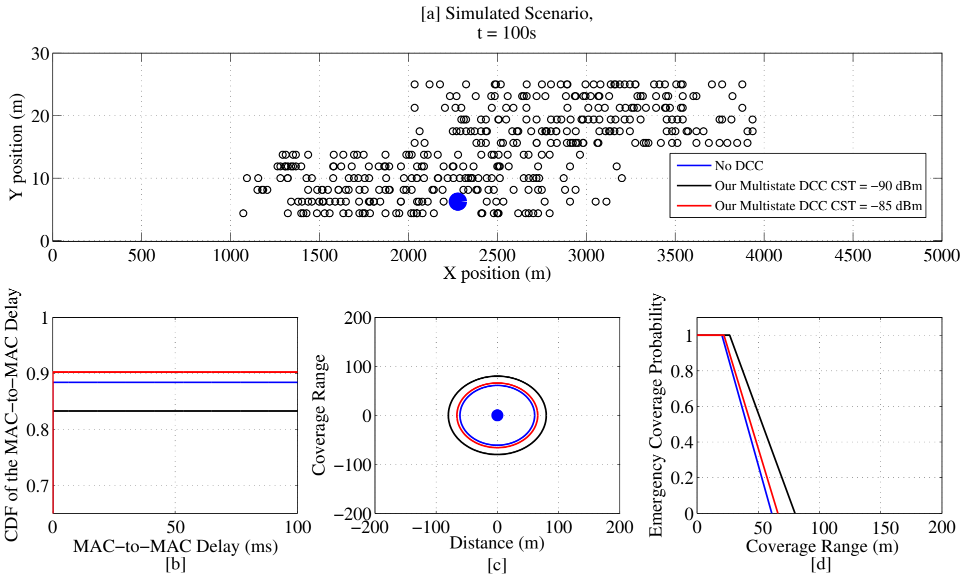

Fig. 16. Simulation Results for a Vehicle initialized in *Relaxed State* (t=100 s) for CST−85 dBm

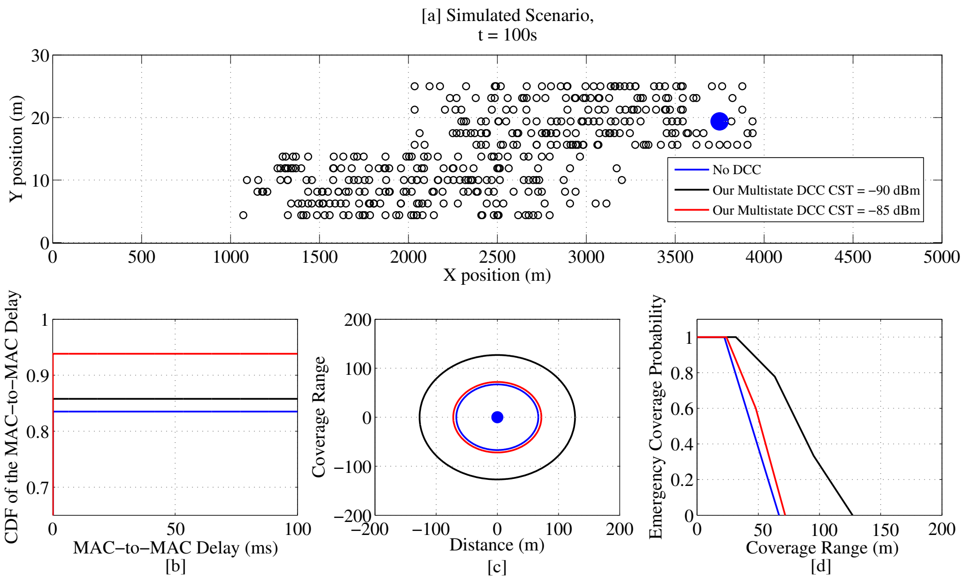

Fig. 17. Simulation Results for a Vehicle initialized in *Restrictive State* (t=100 s) for CST−85 dBm

Tab. XIX displays the results for a vehicle initialized in *active state*, and it reflects how reliability can be enhanced (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 XIX
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 DCC $CST = -90\ dBm$	(0.95, 91 m)
Multistate DCC $CST = -85\ dBm$	(0.97, 85 m)

And for a vehicle initialized in an already heavy-loaded scenario, so having the more conservative initial parameter setting (vehicle initialized in *restrictive state*), the current multistate outperforms the rest but reliability threshold is not yet achieved, as shown in Fig. 19b and in Tab. XX.

2) VANET Performance: First overall system results show the performance in terms of reliability and

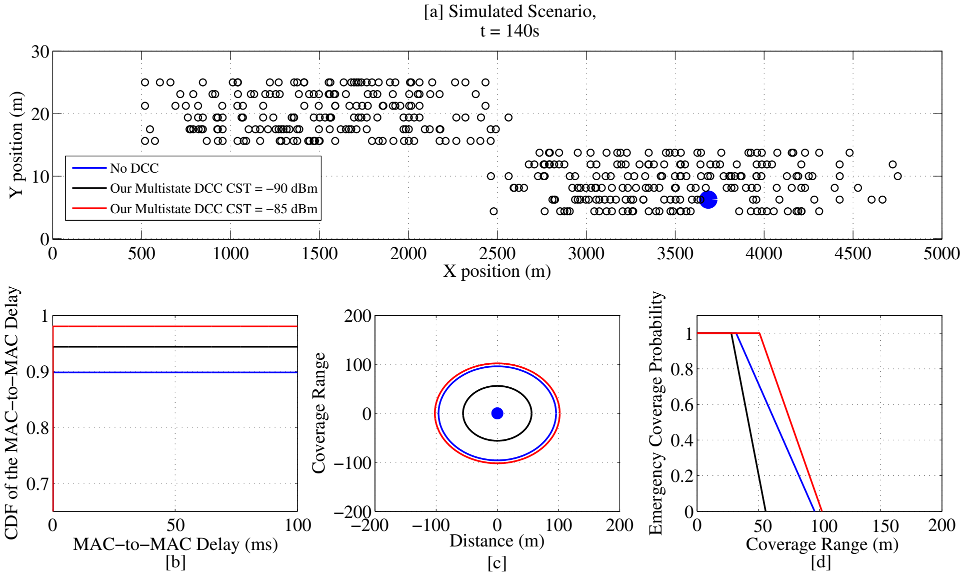

Fig. 18. Simulation Results for a Vehicle initialized in *Relaxed State* (t=140 s) for CST−85 dBm

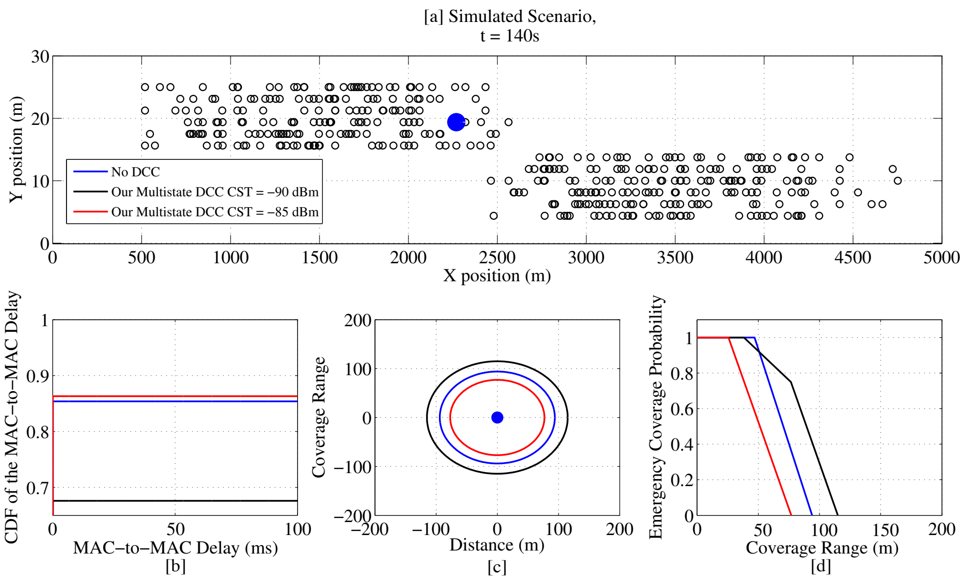

Fig. 19. Simulation Results for a Vehicle initialized in *Restrictive State* (t=140 s) for CST−85 dBm

TABLE XX
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 DCC $CST = -90\ dBm$	(0.67, 115 m)
Multistate DCC $CST = -85\ dBm$	(0.86, 77 m)

dependability. Fig. 20 depicts how the multistate active DCC proposal using $CST = -85\ dBm$ reaches not only a reliable but a dependable performance throughout the whole simulation time (see Fig. 20c). 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 last VANET performance results are related to the value of the broadcasted data. 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 bottom-line of this last evaluation is also to compare the TRC performance with the uniform message generation rate. The plain EDCA and three-state design have fixed message generation rate set to 2 Hz, whereas the two multistate

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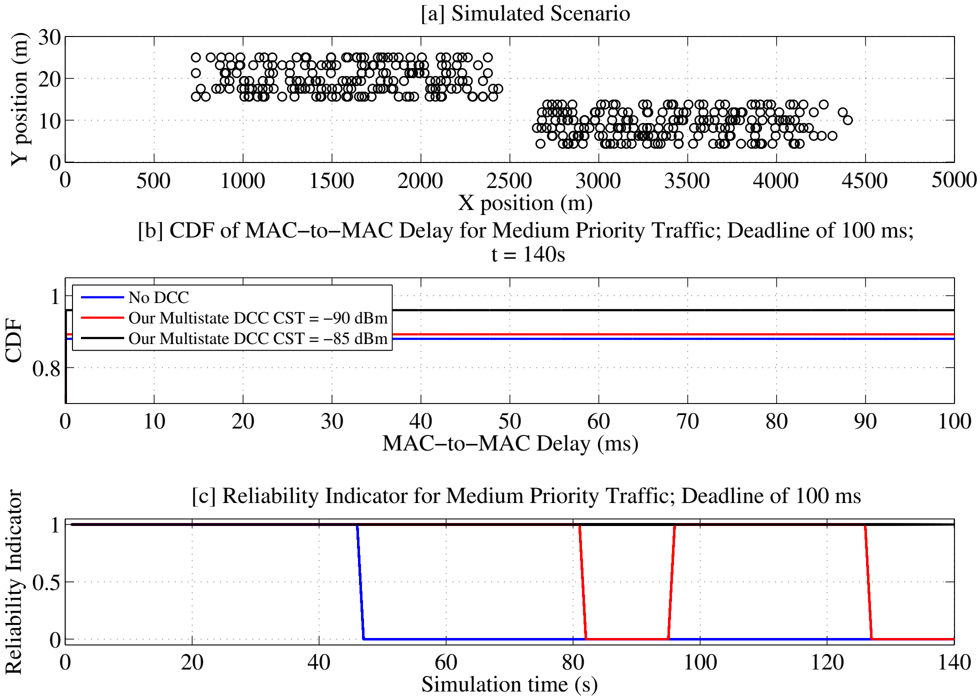

Fig. 20. System Performance for two VANET merging scenario: CDF of MAC-to-MAC Delay and Reliability for $CST = -85\ dBm$

approaches implement TRC. As Fig. 21 shows, the mean freshness for the multistate designs are similar to each other (as both implement the same TRC). This means that the broadcasted data traffic is more up-to-date.

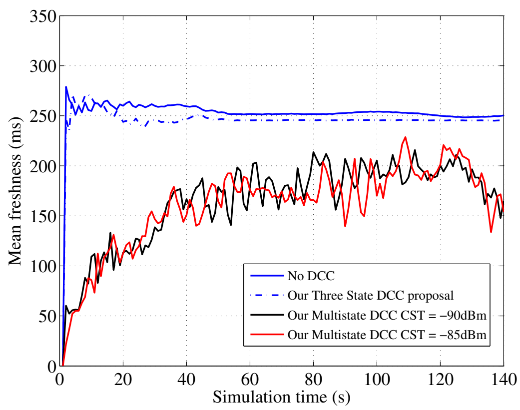

Fig. 21. System Performance for two VANET merging scenario: Data Novelty

The lower levels of the TRC mechanisms in opposition to the fixed-rate solution underline once again the better performance achieved by the adaptive TRC algorithms.

VII. Conclusions

This paper contributes new performance indicators for evaluating MAC performance when scheduling safety-related data and carried out a performance study of a transient vehicular scenario in terms of these safery-relevant performance indicators.

For initially dense (vehicle inter-arrival time is set to 1 s) and dynamic scenarios with variable traffic density (i.e. merging situations), the use of plain EDCA is discouraged. In both cases reliability is lost during the merging situation. For EDCA, even the performance for a 200 vehicles VANET is unreliable. It is only when implementing a cross-layer enhancement, the so called DCC mechanism built on top of IEEE 802.11p MAC, that reliability in terms of delay and coverage range is achieved and even dependability throughout the whole simulation time is reached.

The goal of this contribution was to evaluate not only the MAC-to-MAC reliability but also the dissemination range reliability. Other than that the authors also wanted to evaluate the VANET performance in time, therefore a certain set of performance indicators (DCF of MAC-to-MAC delay for validation and the rat for performance evaluation) have been

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selected. In further work it is planned to work with other sets of performance indicators.

SoTDMA has been discarded for this set of simulations because as mentioned in the paper, by implementing EDCA with lower data traffic priorities SoTDMA performance is reached (in terms of CDF of MAC-to-MAC delay) in congested traffic scenarios. The scope of this work is DCC implemented on top of EDCA but for future work the authors do not discard comparing DCC+EDCA with DCC+SoTDMA.

A. Key Performance Indicators

When scheduling safety-related information it is important that warnings arrive timely and that they are disseminated as far as collision-free coverage allows, so the drivers can anticipate to the danger ahead. In previous work reliability has been only evaluated in terms of *cumulative distribution function of the MAC-to-MAC delay ($CDF(\Delta t)$)*. This work has presented the complementary distribution showing the dissemination range (Δd) and the reliability in terms of *complementary cumulative distribution function of the coverage range (($CCDF(\Delta d_{FRAME})$))*. The tuple ($CDF(\Delta t), \Delta d$) provides the complete description of reliability. By evaluating the temporal evolution of a reliability, a dependability indication has been obtained. Instead of instantaneous performance, a QoS performance study has been achieved.

On the other hand, this work has also provided performance indicators for evaluating the transmit rate control algorithm within the decentralized congestion control mechanism (*freshness of the information*). Results have shown that an adaptive TRC provides a more updated information, in contrast to no TRC performance.

B. Performance of MAC Layer for Traffic-Safety

The evaluated scenario in this contribution is the merging situation of two internally well-organized VANETs. The impact of traffic density *variation* is the effect under study. EDCA displays 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. Results have shown how the best transmit power control results are achieved when states are designed related to the channel load. 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 certain stabilization time until reliable performance is regained. And then again when both VANETs begin to separate, the transient effect reappears. These accumulative effects present in transient vehicular scenarios can be 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 can synchronize to set a common parameter setting (make a joint decision) so that the overall VANET performance is enhanced. Another option is tuning the CST. This work displays the results for the second option. Curves have shown that dependability is reached by using our proposal multistate active DCC mechanism when the CST sensitivity is increased to -85 dBm. With that parameter setting coverage ranges are enhanced 5 to 10 m in comparison to plain EDCA performance, reaching 60 to100 m coverage range for a QoS (0.9,100 ms).

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