IEEE WCNC 2017, San Francisco, CA, USA, March 2017

Evaluation of Multi-hop Packet Prioritization for Decentralized Congestion Control in VANETs

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***Abstract*—Decentralized congestion control (DCC) in ITS-G5 based vehicular ad hoc networks ensures that the requirements of safety and traffic efficiency applications are met even under high vehicle density and channel load conditions. In European standardization, a "gatekeeper" on top of the ITS-G5 MAC sub-layer is being considered that controls a node's packet rate as a function of the channel load. This paper studies the performance of the gatekeeper with packet prioritization and an adaptive linear control algorithm. The simulation results indicate that the gatekeeper with priority queuing (PQ) can effectively handle different packet priorities for multi-hop packets. Our gatekeeper-specific enhancements of the forwarding algorithm yield performance improvements in terms of reliability and latency compared to the plain DCC approach. Finally, we discuss the issue of packet starvation caused by the gatekeeper's PQ scheme that affects the performance of lower-priority packets.**

I. Introduction

Congestion control is a key functionality in communication networks, in which packet flows share the network resources in terms of link bandwidth and buffer space. It ensures high throughput and low delay, facilitates a fair share of resources and avoids congestion collapse in overloaded conditions. Conventional approaches for congestion control include end-to-end and network-assisted approaches, whereas in the latter case the network components provide feedback to the source regarding the congestion state. These conventional approaches cannot be directly applied to wireless vehicular ad hoc networks (VANETs) because in VANETs every node acts as end device and network component at the same time. In addition, VANETs are self-organized and therefore require a *de-centralized* congestion control (DCC) approach. It is also important noting that safety and traffic efficiency applications considered in VANETs have strict requirements on latency, reliability and throughput. It is inherent to the underlying WiFi-based radio that high vehicle densities result in a degraded performance and require to keep the load on the wireless channel below a threshold.

DCC has been subject of research for several years, whereas most of the proposed algorithms focus on DCC for periodic, single-hop broadcast messages. In the DCC algorithm in [1][2], each vehicle adapts its message rate in such a way that the total channel load converges to a pre-defined target. [3] applies transmit power control in order to adjust the communication range and limit the load below a target. Authors in [4] combine transmit power and message rate control. The paper in [5] suggests awareness control, a variation of DCC where the algorithm to control the message rate takes both channel load and application requirements into account.

Though being an active research topic DCC has already been addressed in standardization for vehicular communication to ensure that DCC will be part of the initial deployment for these systems; see [7][8] for an overview of standards for vehicular communication systems in US and Europe. The European system – also referred to as Cooperative Intelligent Transport Systems (C-ITS) – defines a cross-layer framework for DCC. This framework introduces a central DCC function, which enforces the rate with which a node (vehicle or roadside unit) injects data into the network. Essentially, this function – also termed *DCC-gatekeeper* – throttles the data rate depending on the congestion state of the wireless channel. The position of the DCC-gatekeeper in the protocol stack (Fig. 1), which is on top of the IEEE 802.11-based ITS-G5 and beneath the GeoNetworking protocol [9], ensures that the assigned rate applies to both: the data packets generated by the node and those forwarded by GeoNetworking. While the DCC-gatekeeper in its current version is foreseen for operation on a single channel, it can well be applied for offloading of data between channels in future multi-channel systems.

The DCC-gatekeeper can severely impact the performance of networking and facilities layer protocols, as well as the application performance. Queuing delays and packet drops can result in long end-to-end delay and high message loss rate, respectively. These effects can vary for different classes of messages, considering that the DCC-gatekeeper maintains several queues for messages with different priority levels. In such a multi-queue system queued low-priority packets may starve, causing further increasing latency and loss rate for these packet types.

In this paper we study the impact of the DCC-gatekeeper on the performance of vehicular communication, focusing on the interaction among queues. In contrast to previous work on DCC algorithms in [1] - [5] and on the standardized DCC framework [6], in this paper we consider multi-hop communication. We extend our work in [10], where we proposed enhancements for DCC-gatekeeper – called "DCC Advanced" – by that the contention-based forwarding algorithm can cope with long access layer delays caused by the DCC-gatekeeper. Based on this algorithm, we evaluate the performance of multi-hop communication in VANETs with different priorities, considering the effects of the multi-queue DCC-gatekeeper. In addition, we present an improved version of our forwarding algorithm in [10].

The remainder of this paper is as follows: Sec. II provides details of the DCC-gatekeeper. Sec. III gives an overview of the base algorithms relevant in the context of this work. Then,

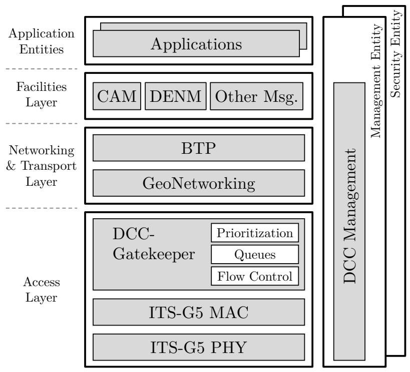


Fig. 1. DCC-gatekeeper at the access layer of the C-ITS protocol stack.

we define the scenario, metrics and simulation parameters of the performance evaluation in Sec. IV and present the results of the evaluation in Sec. V. Sec. VI concludes the paper.

II. DCC-Gatekeeper

The DCC-gatekeeper is a function of the C-ITS protocol stack (Fig. 1) that limits the packet rate at which a node is allowed to transmit. The rate is determined by a control algorithm which takes the instantaneous channel load as input and adapts the packet rate such that the total channel load remains below a pre-defined target. The DCC-gatekeeper is effectively a traffic shaper which outputs the packets at a defined packet rate and retains excess packets. Internally, the DCC-gatekeeper handles packets according to their priority, which is determined by their traffic class. This mechanism enables to categorize messages by their type and to separate messages of the same type but different priorities, specifically for CAM and DENM, i.e., periodic single-hop and event-driven multi-hop safety messages in the C-ITS protocol stack.[1]

The DCC-gatekeeper can be modeled as a multi-queue, single server system with four queues of limited size (Fig. 2). The arrival rate at the queues is determined by two processes: *(i)* the rate at which the node generates messages locally and *(ii)* the rate of forwarded data packets. The service rate is determined by a control algorithm based on the locally-measured channel load, and queued packets have a limited queuing time.

Next, we describe the four main components of the DCC-gatekeeper as it is considered in the DCC framework of C-ITS, specifically in ETSI TS 102 687:[2]

DCC Prioritization categorizes the packets into three main classes: high-priority DENM, regular DENM, CAM and other messages. The classification utilizes the *traffic class* parameter that is passed with the message from the facilities layer. The packets are prioritized in ascending order of the traffic classes and assigned to the DCC queues. Packets in Q_0, i.e., high-priority DENM, can have an emergency flag (EF) for latency critical messages. Such flagged packets bypass the queue and are directly scheduled without any delay. The priorities of the DCC-gatekeeper are further mapped to the traffic categories

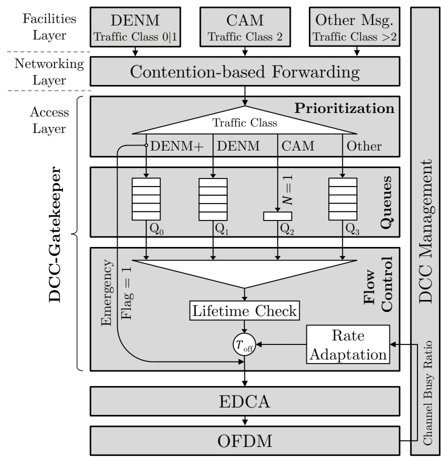


Fig. 2. Queuing system of the DCC-gatekeeper in the context of the C-ITS protocol stack.

at the enhanced distributed channel access (EDCA) of ITS-G5 (see Sec. III and the EDCA-related parameters in Tab. I).

DCC Queues consist of four FIFO (First in first out) drop-tail queues ($Q_0 \dots Q_3$) with different priorities, whereas Q_0 has the highest priority. Queue Q_2, which is used for CAM, has a size of one only since it is counterproductive to forward outdated CAMs. In other words, a newly arriving packet replaces a queued one.

DCC Flow Control[3] schedules packets from the DCC queues, considering the priorities and the adaption of the packet transmission rate. The de-queuing follows a priority queuing (PQ) model, where the packet from the head of the highest-priority queue is de-queued first. When a packet is de-queued and its maximum queuing time is expired it is discarded and the next packet is immediately de-queued. It is worth noting that in every cycle only a single packet is de-queued; this is in contrast to the EDCA queues, where the individual queues schedule packets independently. A packet from a lower-priority queue is scheduled if the higher-priority queues are empty. PQ is a simple scheme with inherent limitations: if any of the higher-priority queues are filled, a lower-priority queue faces a complete resource starvation. In this case, packets are discarded, either because they have exceeded their maximum queuing time or the queue space allocated for the low-priority queue starts to overflow.

Furthermore, the DCC flow control adapts the packet rate, i.e., the equivalent to the service rate of a queuing system to remain below the predefined threshold of the channel load. The channel load is provided by the DCC management entity and used to compute a parameter T_{off}, i.e., the delay between two subsequent packets. T_{off} is the inverse of the packet rate and literally the time during which the "gatekeeper" closes its gate and retains packets. If T_{off} is increased and less packets are sent, the channel load will decrease.

Rate Adaptation refers to the algorithm to determine instantaneous packet rate. In this paper we apply LIMERIC, which is an adaptive control algorithm [1][2] with suitable properties

[1] Cooperative Awareness Message (CAM) and Decentralized Environmental Notification Message (DENM), standardized in ETSI EN 302 637-2 and -3.

[2] ETSI TS 102 687 has already been published, but is currently under major revision. The DCC-gatekeeper concept is described in the current version.

[3] We note that in common literature about data traffic management the term *flow control* is clearly separated from *congestion control*. However, in this paper we stick to the notion introduced in ETSI TS 102 687, which considers flow control as a synonym for the queue's service discipline.

TABLE I. MESSAGE TYPE PARAMETERS CONSIDERED IN SIMULATION

Parameter	High-priority DENM (DENM+)	Regular DENM	CAM
# of transmitting vehicles	2 %	30 %	100 %
Sent packets per vehicle	10	90	200
Transmit interval	1 s	1 s	0.5 s
Priority	high	medium	low
Traffic class (TC)	0	1	2
EDCA access category	AC_VO	AC_VI	AC_BE
DCC-gatekeeper queue #	Q_0	Q_1	Q_2
Queue size	400	400	1
Maximum queuing time	10 s	10 s	10 s
Forwarding	multi-hop	multi-hop	single-hop

for the computation of T_{off} in particular with respect to stability and convergence. We modify the base algorithm from [1] to determine T_{off} using the channel busy ratio CBR (see also Sec. IV) as parameter for the channel load. Eq. (1) is more general than the proposed equation in the current version of ETSI TS 102 687 V1.1.2, where the total packet rate in the channel is taken into account instead the CBR. The next packet rate $r_i(t_{k+1})$ for node i is computed as follows:

$$r_i(t_{k+1}) = (1-\alpha)r_i(t_k) + \frac{\beta}{T_{\text{on}}}\left(CBR_{\text{th}} - CBR_i(t_k)\right), \quad (1)$$

$$T_{\text{off},i}(t_{k+1}) = \frac{1}{r_i(t_{k+1})}, \quad (2)$$

where $r_i(t_k)$ is node i's current packet rate and $T_{\text{off},i}(t_{k+1})$ is the duration of time the DCC-gatekeeper will wait until it passes the next packet to the EDCA. $CBR_i(t_k)$ indicates node i's current channel busy ratio. α is the exponential forgetting and β the scaling factor, both being constant. T_{on} refers to the transmission time, i.e., the time it takes to transmit the packet over the air. For details on LIMERIC we refer to [1].

III. BASE ALGORITHMS EDCA, DCC PLAIN, CBF AND RORA

This section gives a brief description of the base algorithms EDCA, DCC Plain, RORA and CBF, which helps understanding the scenario and results of the DCC-gatekeeper evaluation.

Enhanced Distributed Channel Access (EDCA) is the base access scheme for ITS-G5 MAC, which relies on carrier sense multiple access and collision avoidance (CSMA/CA). EDCA has four independent queues with different priorities, which are realized by queue-specific lengths of inter-frame spaces (AIFS) and contention windows (CW). The priorities can be found in TABLE I. EDCA is used in the DCC protocol stack beneath the DCC-gatekeeper (Fig. 2).

DCC Plain applies the sole functionality of the DCC-gatekeeper with prioritization, queuing and flow control as described in Sec. II, but without the extensions for RORA that will be introduced below. DCC Plain is part of the DCC framework standardized in ETSI TS 103 175 V1.1.1. and the baseline DCC algorithm used as reference in this paper. Key feature of the DCC Plain is that the algorithm handles all message types, including single-hop and multi-hop. It complements facilities-layer DCC schemes that adjust the generation rate of CAM and enables to control also forwarded packets, which can cause a considerable congestion on the wireless channel.

Contention-based forwarding (CBF) is a robust multi-hop forwarding algorithm with two key features. First, CBF takes a receiver-based decision whether to forward or discard a packet. Second, it provides a high degree of efficiency in the multi-hop packet distribution. With CBF it is not necessary that every vehicle in communication range forwards its packet. Instead, the vehicle with the maximum progress, i.e., the maximum distance to the sender, forwards the packet; the others suppress the retransmission. The first feature is achieved by a timer with a duration that depends on the distance between the sender and forwarder. The longer the distance the shorter the timer. The second feature is accomplished by "overhearing", which enables vehicles to listen to all transmissions on the wireless channel and maintain a packet duplication list. If a packet is received a second time, i.e., a packet duplicate is detected, the vehicle is going to discard the received packet and refrains from forwarding its locally buffered packet copy. In summary, CBF relies on the two mechanisms – timeout and overhearing. If any of the two mechanisms break, CBF is going to fail.

Problem statement: in scenarios with a high vehicle density and channel load the DCC-gatekeeper introduces an extra delay T_{off} in the processing of a packet from networking to access layer in order to control the packet rate. With growing queuing time at the DCC-gatekeeper the processing delay gradually overturns the CBF timer and destroys CBF's overhearing. At some point, the CBF will completely break and transmitted multi-hop packets are inefficiently retransmitted by each vehicle. Eventually, the flooding of the network, also commonly known as broadcast storm in VANETs, causes a highly saturated channel. Under such conditions, a reliable and rapid distribution of any type of message cannot be guaranteed.

In saturated channels, when LIMERIC controls the DCC-gatekeeper's packet rate, two cases exist where the delay of the DCC-gatekeeper can exceed the maximum CBF timeout $t_{\max}$: *(i)* the gatekeeper's off-time $T_{\text{off}} > t_{\max}$ and *(ii)* the dwell time of packets in the DCC-queues is longer than $t_{\max}$. In both cases, the timer of the vehicles in communication range expire, all packets are passed to the vehicles' DCC-gatekeepers and will eventually be retransmitted.

Robust Overhearing Recovered Algorithm (**RORA**): In DCC Plain there is no possibility to prevent the duplicates from being passed to the ITS-G5 MAC sub-layer. For this reason, we extend DCC Plain and enable DCC flow control to access the packet duplication list of CBF. With this enhancement, DCC flow control can drop packets if a duplicate is detected.

DCC queues store packets until they are permitted to be transmitted. During this time if a duplicate packet is arrived, it is logged in the packet duplication list. When the packet in the queue is dequeued by DCC flow control it can be recognized as duplicate and is discarded. Thus, packets are refrained by erroneous forwarding and the overhearing functionality of CBF is recovered.

We have already studied the impact of the DCC-gatekeeper on CBF in [10] and have shown that the malfunctioning of CBF can be resolved in combination with an enhanced DCC-gatekeeper algorithm. In this paper, we use a further optimized version: when DCC flow control discards a duplicate packet, it immediately fetches another packet from the DCC queues and processes it, instead of waiting for the next cycle. The optimization avoids instabilities in the LIMERIC algorithm and yields a better performance. We will show the performance

TABLE II. SIMULATION PARAMETERS

Parameter	Values
Vehicle density	5-60 $veh/km/lane$ (18.3 km, 3+3 lanes)
Access layer protocol	ITS-G5 (IEEE 802.11 OCB)
Data rate	6 Mbit/s
Transmit power & antenna gain	20 dBm + 9.1 dB
Channel bandwidth	10 MHz at 5.9 GHz
Path loss model	ThreeLogDistance: channel exp. 1.9 - 3.8
Fading model	Nakagami-shape factor 1
Simulation duration	100 s
CAM, DENM, DENM+ size	512 bytes
Geographical area	1,500 × 100 m behind the vehicle
LIMERIC: α | β | T_{on} | CBR_{th}	0.01 | 0.001 | 872 μs | 0.65
LIMERIC: $T_{\text{off,min}}$ | $T_{\text{off,max}}$	10 ms | 1000 ms

gain in this paper but cannot provide details of the instabilities due to space constraints.

IV. Evaluation Scenario, Metrics and Simulation Parameters

This section defines the scenario, metrics and simulation parameters for the performance evaluation. The objective of the performance evaluation is to validate that the DCC-gatekeeper is able to prioritize the data traffic, to control the packet rate such that the total load converges to a target threshold and to effectively handle multi-hop packets with different priorities.

For the simulation, we assume a typical freeway with communicating vehicles and consider different vehicle densities. All vehicles are equipped with communication technologies based on ITS-G5. We distinguish among three types of messages with different priorities: CAM broadcast status data and informs the surrounding vehicles about the ego-vehicle's position, speed and heading. Regular DENMs are event-driven safety messages, which can be triggered by different applications. High-priority DENMs will be sent if a safety-of-life situation occurs and the vehicles in the vicinity need to be informed rapidly and reliably, e.g., about a hazardous location and therefore we also set the emergency flag EF (see Fig. 2).

In the considered scenario, all vehicles send CAM from the beginning of the simulation. 30 % of vehicles start generating regular DENMs after 5 s simulation time and stop sending them 5 s before the simulation ends. 2 % of vehicles send 10 high-priority DENMs with an interval of 1 s. They start to generate the high-priority messages uniformly distributed between 15 and 75 s simulation time, which should address vehicles, detecting a dangerous situation. We have summarized the parameters related to the message dissemination in Tab. I.

The vehicle densities in the simulation scenario are taken from the German freeway A8 with 5 - 60 veh/km/lane [11] with 6 lanes, 3 lanes in each direction. The vehicles drive with a maximum speed of 120 km/h. The geographical area for the dissemination of multi-hop messages is 1,500 × 100 m behind the originating vehicle. Vehicles located outside the area discard received messages. The mobility is modeled with the well-known road traffic simulator SUMO[4] to generate traces for the movement.

The simulation is performed with the network simulator ns-3[5], version 3.23. We use the C-ITS protocol stack with ITS-G5 for the access layer (ITS-G5 PHY and MAC) and install

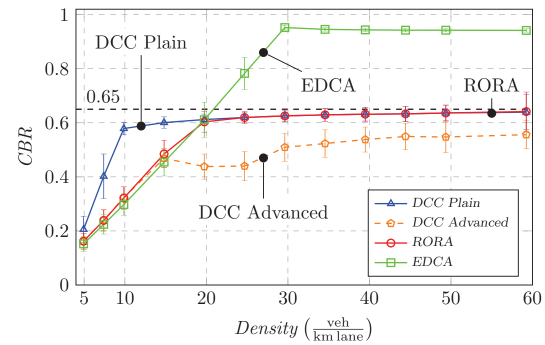


Fig. 3. Channel busy ratio (CBR) over vehicle density. DCC Plain and RORA keep the load below the threshold of 0.65, whereas DCC Advanced and EDCA converges to a CBR of 0.55 and almost 1, respectively. DCC Advanced is the predecessor of RORA.

them on all simulated vehicles. Additionally, we have added components for the DCC-gatekeeper, CBF, CAM, regular and high-priority DENM (see Fig. 1). The channel is simulated with a log-distance stochastic Nakagami fading model [12], a commonly accepted model used for simulations of wireless vehicular communication. The chosen parameters yield a communication range from 200 m with 95 % packet success ratio to 600 m with 10 % packet success ratio. A summary of all simulation parameters can be found in Tab. II.

For the evaluation and comparison of the algorithms DCC Plain, RORA and EDCA, we defined three metrics.

Average Channel Busy Ratio (CBR) measures the average channel load and provides the ratio of the average channel busy time in an interval T. The physical layer measures the channel as busy when the received signal strength S is above a predefined threshold S_{th} ($S > S_{\text{th}}$). CBR is computed by:

$$CBR = \frac{1}{K}\sum_{i=1}^{K}\frac{t_{\text{busy},i}}{T} = \frac{1}{K}\sum_{i=1}^{K}\frac{t_{\text{busy},i}}{t_{\text{busy},i}+t_{\text{idle},i}}, \quad (3)$$

where $t_{\text{busy},i}$ and $t_{\text{idle},i}$ is the fraction of time when the channel is sensed busy ($S > S_{\text{th}}$) and idle ($S < S_{\text{th}}$), respectively, of vehicle i. K is the number of vehicles. For example, if the measuring interval $T = 200$ ms and the channel is sensed busy for $t_{\text{busy},i} = 150$ ms, we yield a CBR_i of 0.75.

Vehicle Coverage Ratio (VCR) is a measure for the successfully reception of multi-hop messages in a geographical area. In GeoNetworking the vehicles set up a geographical relevance area where services distribute messages, e.g., for road works warnings or traffic jam ahead warnings. The VCR measures the amount of vehicles who receive the message correctly, e.g., if 10 vehicles are inside the geographical area and 8 vehicles receive the message we have a VCR of 80 %:

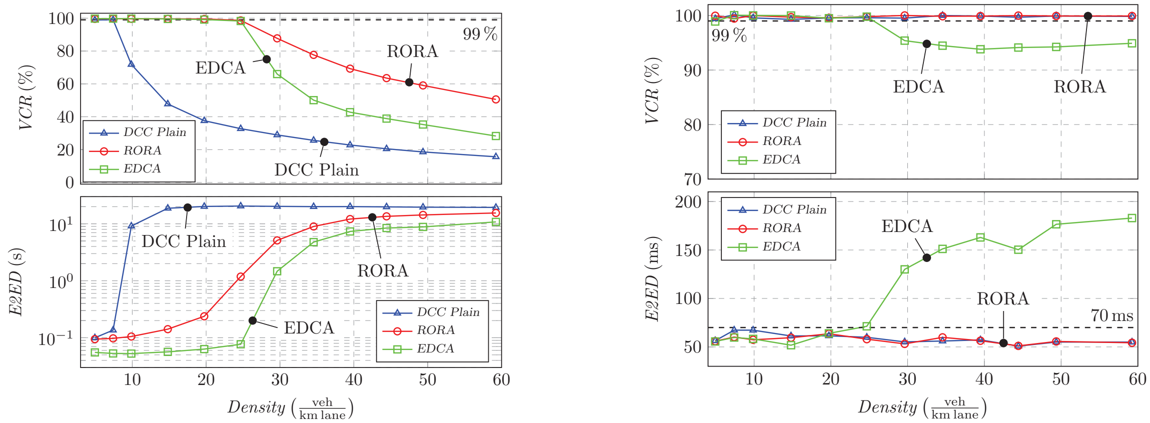
$$VCR = \frac{\text{No. of receiving vehicles in geo-area}}{\text{No. of all vehicles in geo-area}}. \quad (4)$$

Average End-to-End Delay ($E2ED$) measures the average time until a vehicle in the geographical area receives a multi-hop message. For this the time is measured when a multi-hop packet is generated $t_{\text{Tx},i}$ by the source until it is received by the destination $t_{\text{Rx},i}$ including all hops, averaged over all received messages N:

$$E2ED = \frac{1}{N}\sum_{i=1}^{N}\left(t_{\text{Rx},i} - t_{\text{Tx},i}\right). \quad (5)$$

[4]Simulation of Urban MObility, URL: http://sumo.dlr.de/wiki

[5]URL: http://www.nsnam.org



(a) VCR and average $E2ED$ for regular DENMs.

(b) VCR and average $E2ED$ for high-priority DENMs.

Fig. 4. Reliability and latency for both types of multi-hop DENMs with regular (a) and high (b) priority. (a) DCC Plain decreases in VCR after the CBF algorithm breaks. EDCA and RORA have a great performance up to 25 veh/km/lane. (b) The high-priority DENMs perform extensively better than the regular DENMs as it is expected due to the higher priority in the DCC-gatekeeper and EDCA queues. The VCR for DCC Plain and RORA is beyond 99 % up to highest vehicle densities with remaining low average $E2ED$.

V. Performance Evaluation

This section presents the results of the simulation-based investigations for channel load, reliability and latency.

A. Channel Load

The CBR as a measure of the channel load is shown in Fig. 3 for all algorithms. EDCA has a linearly increasing CBR up to almost 1, whereas the upper limit 1 can never be reached due to the inter-frame spaces in CSMA/CA. From Fig. 3 we can see that DCC Advanced (dashed line, described in [10] and a simplified version of RORA) has a worse channel usage than RORA. The reason is that DCC Advanced waits for the next cycle when a packet is discarded due to duplication detection. In RORA the next packet is immediately taken, therefore more packets are sent and LIMERIC can work more reliable and stable. From Fig. 3 we can derive that LIMERIC works well for DCC Plain and RORA since both schemes approach the threshold CBR_{th}=0.65 (red and blue line in Fig. 3) for densities greater than 20 veh/km/lane. We note that LIMERIC cannot reach CBR_{th} because of the exponential forgetting parameter α. The tracking error [1], i.e., the difference between the target and the measured value depends on the control parameter α and β and the real convergence point CBR_{f} can be computed by:

$$CBR_{\mathrm{f}} = \frac{K \cdot \beta \cdot CBR_{\mathrm{th}}}{\alpha + K\beta}, \tag{6}$$

where K is the number of neighbors, CBR_{th} the desired threshold (0.65), α, β are the exponential forgetting and the scaling factor, respectively. For example, in our case for a vehicle density of 50 veh/km/lane: CBR_{f}=0.634. With increasing density the CBR converges to CBR_{th}:

$$CBR_{\mathrm{f}} \rightarrow CBR_{\mathrm{th}} \quad \text{for} \quad K \rightarrow \infty,$$

which can be seen in the slightly increasing values of CBR for DCC Plain and RORA in Fig. 3.

B. Reliability and Latency

We first present the performance results for regular DENM, followed by high-priority DENM. Finally, we discuss the performance of lower-priority CAM.

Regular DENM: Figure 4a presents the VCR (top) and $E2ED$ (bottom) with DCC Plain, RORA and EDCA. The dashed line with 99 % illustrates the edge when 99 % of vehicles in the geographical area are able to receive the packet. EDCA is regarded as the baseline algorithm: when its CBR approaches 1 vehicles will have a channel access time longer than 100 ms, which is the maximum CBF timeout. Then, the overhearing mechanism of CBF eventually breaks, which results in a decreasing VCR and growing $E2ED$ of up to 10 s. In Fig. 4a, this behavior can be observed for densities greater than 25 veh/km/lane.

We have seen that DCC Plain is capable to keep the CBR below the threshold (see Fig. 3), however, in comparison to EDCA it shows a clearly worse performance in terms of reliability and latency: as it can be seen in Fig. 4a, the first two points in the low density region have a VCR of 99 %, which can be explained with a T_{off} time of less than 35 ms. When T_{off} exceeds 100 ms, which is the maximum timeout for the CBF algorithm, at a vehicle density of about 10 veh/km/lane CBF breaks and packets are forwarded in an uncontrolled manner. Then, two main issues occur: *(i)* the network is flooded with a high number of redundantly forwarded packets and *(ii)* the queue of the DCC-gatekeeper fills up with packets which cannot be detected as duplicates.

With respect to VCR, RORA performs 40 p.p. better than DCC Plain for medium to high vehicle densities thanks to the recovered overhearing functionality of CBF. The worse $E2ED$ compared to EDCA is caused by the "closed" gatekeeper, i.e., T_{off} time, combined with a large queue size. The packets have to wait longer in the DCC queue, which results in a tradeoff between VCR and $E2ED$. Finally, the reason for the decay beyond 25 veh/km/lane is caused by the high number of generated messages exceeding the channel capacity.

High-Priority DENM: Figure 4b depicts the results for high-priority DENMs. We can see that DCC Plain and RORA works well up to very high vehicle densities and stay above a VCR of 99 %, showing that free resources are available and the DCC scheme works properly. The $E2ED$ for RORA and DCC Plain decreases slightly with increasing vehicle density.

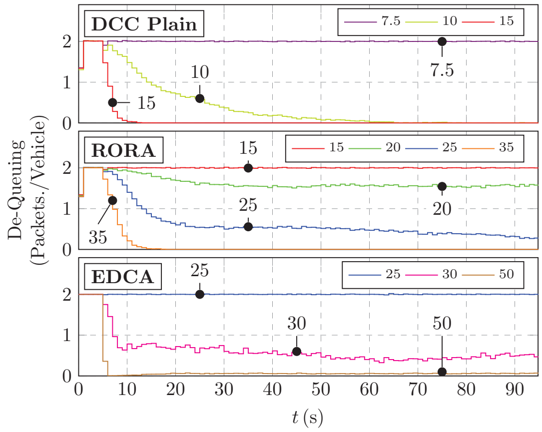


Fig. 5. De-queuing rate over simulation time (in bins of 1 s) of DCC-gatekeeper Q_2-queue with different vehicle densities. The unit in the legend is veh/km/lane. Since the single-hop CAM rate is $2\,\mathrm{pkts/s}$, the ideal de-queuing rate would be 2. Beyond a certain density the CAM rate approaches zero for all algorithms.

With increasing vehicle density the probability that vehicles which are further away receive a message error free increases and therefore, have a shorter timeout. Beyond $25\,\mathrm{veh/km/lane}$ VCR of EDCA drops down to $95\,\%$ and $E2ED$ increases to $175\,\mathrm{ms}$ due to the congested channel, which is regarded to be unacceptable for high-priority safety-of-life messages.

CAM: The DCC-gatekeeper applies a simple priority queuing (PQ) for the de-queuing mechanism, which causes problems with lower priority queues. Figure 5 depicts the Q_2 queue de-queuing rate of DCC Plain, RORA and EDCA over the simulation time in bins of $1\,\mathrm{s}$. The transmission of DENMs start at $5\,\mathrm{s}$, hence in the first $5\,\mathrm{s}$ only CAMs are transmitted. We can observe that beyond a particular vehicle density the transmission of CAMs is completely withheld. In the case of DCC Plain, CAMs are sent up to a density of $7.5\,\mathrm{veh/km/lane}$. For $10\,\mathrm{veh/km/lane}$ the CAM rate slowly decreases to zero and for $15\,\mathrm{veh/km/lane}$ the CAM rate drops down to zero as soon as the first DENMs are transmitted. RORA is more robust than DCC Plain and CAMs can be sent up to $25\,\mathrm{veh/km/lane}$. Interestingly, with EDCA a vehicle is able to send CAMs also for higher densities due to the different de-queuing scheme of EDCA. However, beyond $50\,\mathrm{veh/km/lane}$ EDCA almost refrains from sending CAMs.

Albeit in this paper we focus on the impact of the DCC-gatekeeper on multi-hop messages with different priorities, the timely and reliable transmission of single-hop CAMs is a fundamental requirement for C-ITS and basis for various use cases. The starvation of CAMs in the DCC-gatekeeper queue is an inadmissible behavior of the DCC-gatekeeper de-queuing scheme. From the results of the performance evaluation we can conclude that additional mechanisms to secure the CAMs performance are required.

An alternative is to replace PQ by a less strict scheduling algorithm, such as Weighted Fair Queuing (WFQ) that allows to assign a weighted fraction of the overall link capacity to the CAM queue. However, a systematic analysis of CAM performance optimization in a multi-queue gatekeeper and message priorities is beyond the scope of this paper and regarded as future work.

VI. Conclusion

In this paper we have evaluated the performance of C-ITS congestion control based on access layer "gatekeeping", as it is considered in the European standardization process. We have verified that the gatekeeper is able to effectively handle packet priorities for multi-hop packets. The proposed DCC algorithm with cross-layer interaction between the DCC-gatekeeper and contention-based forwarding, RORA, improves the performance of regular DENMs in terms of latency ($E2ED$) and reliability (VCR) compared to DCC Plain. We have shown that high-priority DENMs result in shorter $E2ED$ and higher VCR than regular DENMs: high-priority DENMs achieve a VCR above $99\,\%$ and an $E2ED$ below $70\,\mathrm{ms}$. The simple priority queuing (PQ) scheme of the DCC-gatekeeper results in packet starvation for lower-priority packets beyond a vehicle density of 10 and 35 veh/km/lane for DCC Plain and RORA, respectively. This effect particularly impairs the CAM performance and requires improvements of the DCC-gatekeeper queuing scheme.

Acknowledgment

The research leading to these results has received funding from the European Union Seventh Framework Programme (FP7/2007-2013) under grant agreement n° 619555 - "RESCUE".

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