DCC performance analysis

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Content

1 Abstract

The C2C-CC system supports safety relevant data services, which require high reliability and low latency transmissions. Hence, a Decentralised Congestion Control (DCC) mechanism is needed to control the number of messages on the channel even for high vehicle densities. To support the deployment of Day One application, an appropriate, but simple DCC mechanism needs to be specified.

The performance of three different implementations of the Day One DCC access functionalities will be compared in a highway scenario with a traffic jam considering both CAM and DENM transmissions. The two DCC variants proposed in the DCC white paper v0.5 and version 1.1 are implemented as DCC variant A and B. A third alternative called DCC variant C is proposed, which applies an additional transmit duty cycle limitation to low priority packets. The document describes the C2C simulator framework, introduces the performance metrics such as packet latency, collision rates, position error and duty cycle per vehicle as well as summarises the simulation results for low, medium and high vehicle densities. A comparison of the three different implementations favours DCC variant C due to a small position error and low latency similar to DCC variant A, but a limited duty cycle per vehicle, which contributes to the coexistence of C-ITS systems.

2 Introduction

Data traffic control is an important part of the C2C communication system as safety relevant information needs to be transmitted with low latency and high reliability even in situations with high vehicle densities. As communication takes place in an ad-hoc network without central control decentralised congestion control (DCC) is required. Due to the high mobility of the participants the DCC algorithm has to cope with fast changing channel loads. Two DCC variants have been proposed by the C2C-CC, which have been published in the DCC white paper version 0.5 [4] and version 1.1 [2], respectively. The performance of these two algorithms will be analysed in an application scenario with a pure CAM transmission phase in the beginning, followed by a phase with additional DENM transmissions according to triggering conditions defined for Day One use cases. Different vehicle densities will be assumed to check the DCC behaviour for various channel loads. Furthermore, a third DCC variant is proposed and compared to the two white paper variants.

The analysis uses the IMST framework for C2C simulations, which is shown in Figure 2-1. The heart of the simulator is an event-driven protocol layer simulator denoted as “Radio Link Emulator” or RLE in its short form.

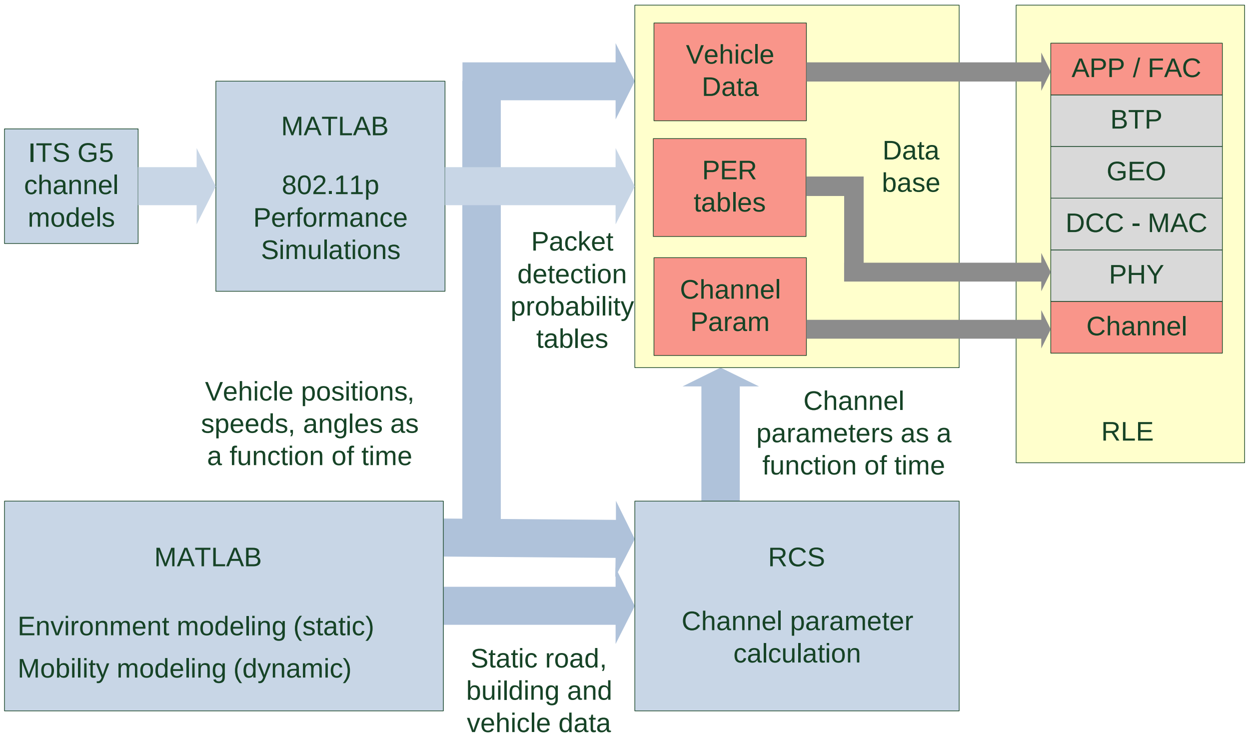


Figure 2-1: IMST framework for C2C simulations

The RLE implements the Car2X protocol stack and considers the following layers:

- BTP (EN 302 636-5-1 V1.2.1)
- Geo networking (EN 302 636-4-1 V1.2.1)
- DCC (DCC Whitepaper V0.5 and V1.1, TS 102 687, TS 102 724)
- 802.2 LLC / 802.11p MAC
- 802.11p PHY: Packet detection probability tables
- Channel: Link characteristics from RCS

The channel receives link characteristics from the RCS (Radio Channel Simulator) for each link between any two vehicles in the simulation. The PHY decides on a successful packet detection based on detection probability tables, which have been pre-calculated by a Matlab 802.11p

PHY simulation. Finally the application and facilities layer receives information on vehicles dynamics and positions in order to check the trigger conditions for DENM generation and to fill the contents of CAM packets.

The simulation framework will be detailed in section 3 and 4, while simulations results are provided in section 5 for the three different DCC variants and three different vehicle densities. Based on the comparison of simulation results one DCC variant will be proposed for standardisation in section 5.3. Section 6 investigates the impact of parameter settings for the selected DCC variant on the system performance, resulting in a recommendation in section 7.

3 Radio Layer Emulator (RLE) simulator description

3.1 Application and facilities layer

The application and facilities layer of the RLE is responsible for CAM generation considering vehicle dynamics and DCC transmit limitations, where the minimum time interval between two consecutive CAM generations (T_GenCam_Dcc) is provided by the DCC layer as a function of the current channel load. Furthermore, the application and facilities layer generates specific DENM packets (post-crash and traffic jam DENMs) according to the triggering conditions summarized in the Scenario Description document [3].

Triggering conditions and CAM transmit intervals are checked with a sampling interval of 10 ms, whereby the start of the periodic check time is randomly selected for each vehicle. The CAM generation rules described in [9] are repeated below:

1. The time elapsed since the last CAM generation is equal or larger than T_GenCam_Dcc and one of the following ITS-S dynamics related conditions is given:
    a. the absolute difference between current direction of the originating ITS-S (towards North) and direction included in previous CAM exceeds 4°
    b. the current position and position included in previous CAM exceeds 4 m,
    c. the absolute difference between current speed and speed included in previous CAM exceeds 0.5 m/s.
2. The time elapsed since the last CAM generation is equal or larger than T_GenCam and equal or larger than T_GenCam_Dcc.

Thereby, the CAM interval is maintained for N_GenCAM =3 successive CAM transmissions except point 1 requires an earlier CAM transmission. After that the CAM interval is reset to the maximum value of 1000 ms.

The packet length and duration of CAMs, post-crash and traffic jam DENMs used in the simulations are summarized in Table 3-1.

Type	Length [Octets]	Packet duration [ms]
CAM	269	0.48
“Traffic jam ahead”	1500	2.144 ms
“Stationary vehicle warning”	1500	2.144 ms

Table 3-1: Packet lengths and durations

3.2 Networking & Transport layer

The GeoNetworking layer is implemented as defined in EN 302 636-4-1 [7]. According to the basic system standards profile [8] the basic system in day one is not required to offload packets to another channel (GN9). Hence all packets are transmitted on the control channel (CCH). Furthermore, the forwarding algorithm specified in Annex E.3 is implemented (GN13). The maximum hop limit is set to 10. All forwarded packets will use the DCC profile DP3 (GN14). Duplicate packet detection is used in the network and transport layer according to GN15.

3.3 DCC functionalities

3.3.1 DCC state diagram

The DCC state machine is a central element of the investigated DCC proposals in present document. Three basic states are defined in [1], which are *Relaxed*, *Active* and *Restricted*. According to [2] the *Active* State shall contain 5 substates resulting in a total amount of 7 states. The actual DCC state is a function of the current channel load. State changes are triggered if the measured channel loads exceeds or falls below a given threshold for a period of time (section 6.4,[1]). Two different time constants are proposed for up and down ramping:

State machine time constants	Description	Defaults
NDL_TimeUp	Time constant ramping up (more restrictive state)	1 s
$NDL\_TimeDown$	Time constant ramping down (less restrictive state)	5 s

Table 3-2: State machine time constants [1]

The DCC state is increased as soon as the minimum measured channel load exceeds the upper channel load threshold of the current DCC state by NDL_timeUp seconds. On the contrary, the DCC state is lowered if the maximum measured channel load falls below the lower threshold for at least $NDL\_timeDown$ seconds.

An example for a measured channel load and the resulting DCC state changes is shown in Figure 3-1. State changes are observed at 3.2, 6.6, 17.6 and 19.4 seconds. The DCC state remains constant in between 6.6 and 17.6 seconds although the channel load falls below the lower threshold of the *Active 2* state. Nevertheless, the duration of low channel load values was smaller than $NDL\_timeDown$ seconds.

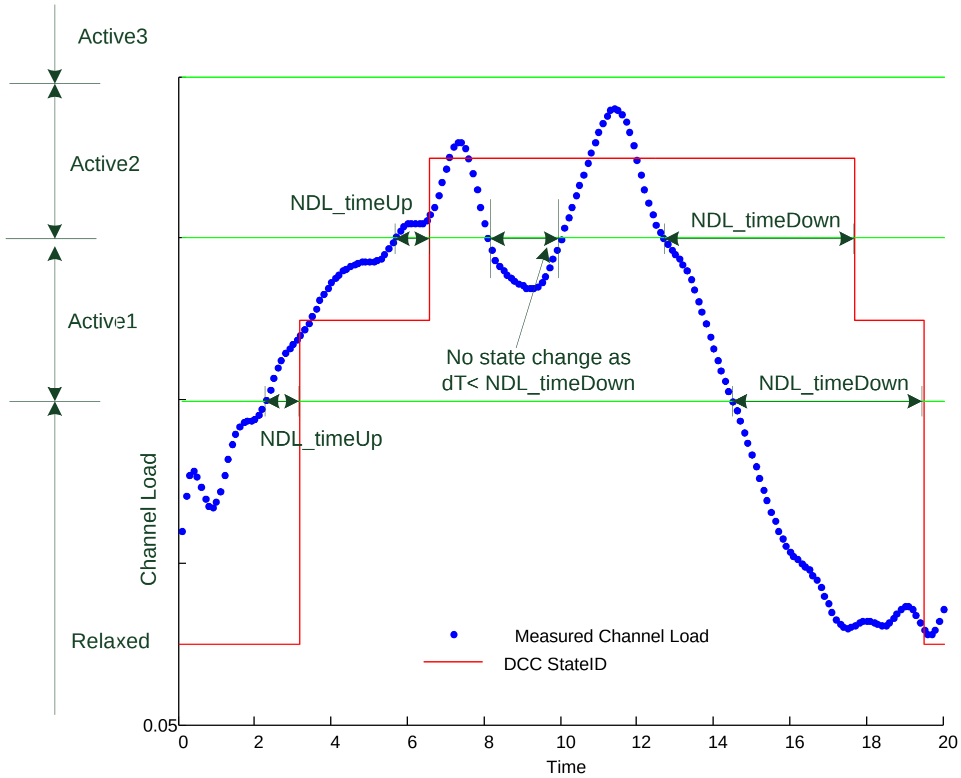


Figure 3-1: DCC state as a function of the measured channel load

Both versions of the DCC white paper ([4],[2]) propose to take the default values of the ETSI approach in Table 3-2 for DCC state transition timing. The corresponding parameters are denoted as T_{up} and T_{down} in Table 2 ([2]). Additionally, Channel Load Smoothing ([2], section 1.3) is applied. The measured channel load is filtered according to

$$CL(t) = 0.5 \cdot ChannelLoad(t) + 0.5 \cdot CL(t-1)$$

The impact of the timing parameter settings will be analyzed in section 5.1, which compares the DCC performance for different values of NDL_timeUp and $NDL\_timeDown$.

3.3.2 DCC variant A

Variant A of the DCC algorithm has been proposed in version 0.5 of the DCC white paper ([4]). This approach considers four DCC queues for the different packet priorities (DP0, DP1, DP2(CAM), DP3) with queue specific minimum packet distances. The parameter settings as a function of the channel state are summarized in Table 3-3.

DP	Relaxed	Active1	Active2	Active3	Active4	Active5	Restrictive
0	95 ms	95 ms	95 ms	95 ms	95 ms	95 ms	95 ms
1	95 ms	111 ms	142 ms	173 ms	204 ms	235 ms	250 ms
2	95 ms	111 ms	142 ms	173 ms	204 ms	235 ms	250 ms
3	95 ms	186 ms	367 ms	548 ms	729 ms	910 ms	1000 ms

Table 3-3: Minimum packet distances in DCC variant A as a function of packet priority and DCC state as proposed in [4]

The corresponding state transition thresholds are shown in Table 3-4.

DCC State	Channel Load (CL)
Relaxed (0)	0% $\leq$ CL<15%
Active1 (1)	15% $\leq$ CL<20%
Active2 (2)	20% $\leq$ CL<25%
Active3 (3)	25% $\leq$ CL<30%
Active4 (4)	30% $\leq$ CL<35%
Active5 (5)	35% $\leq$ CL<40%
Restrictive (6)	40% $\leq$ CL

Table 3-4: State transition thresholds of DCC variant A as proposed in [4]

For all DCC states and the four priority levels a transmit power of 25 dBm is used except for DP3 packets in DCC state Restrictive, where the power level is reduced to 10 dBm.

Due to the queue specific packet rate limitations the earliest transmit time of the next CAM packet just depends on the transmission time of the last CAM. However, DCC informs the facilities layer and the CAM generation module of the current minimum interval between two consecutive CAM generations through the parameter T_GenCam_Dcc (which is exposed by the CAM generation module). This implies that no extra delay is induced by the DCC and CAMs can be forwarded directly to the MAC layer since the CAMs are generated at the facilities layer only when allowed. However, since CAMs are the only packets that adhere to the status of the channel, the other priorities may exhibit delay when arriving at the DCC, see Figure 3-2 where the arrival of two DP1 packets at the DCC is forcing the DCC to delay the second DP1 packet.

In case packets of different priority arrive at the DCC at the same time, they might be both forwarded to the MAC supposed that the distances to the last packets of the same priority are large enough.

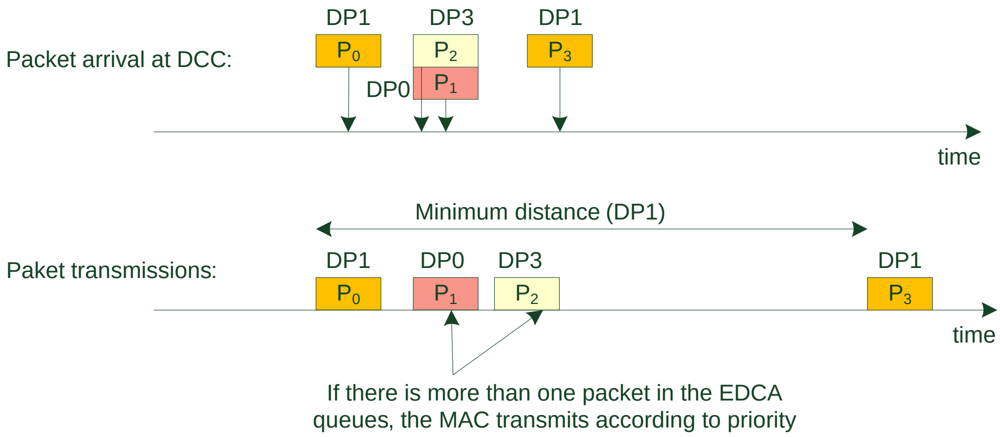


Figure 3-2: Example for the transmission of packets in DCC variant A

The MAC schedules the packet with the highest priority first and then transmits the lower priority packet in case the channel is still free.

3.3.3 DCC variant B

DCC variant B of the DCC algorithm has been proposed in version 1.1 of the DCC white paper ([4]). The sum of all DP1, DP2 and DP3 messages shall meet a common minimum time interval requirement. The minimum transmission interval depends on the actual channel load as summarized in Table 3-5. For all DCC states and the four priority levels a transmit power of 25 dBm is used.

DCC State	Channel Load (CL)	Transmission Interval (T_{OFF})
Relaxed (0)	0% ≤ CL<19%	60 ms
Active1 (1)	19% ≤ CL<27%	100 ms
Active2 (2)	27% ≤ CL<35%	180 ms
Active3 (3)	35% ≤ CL<43%	260 ms
Active4 (4)	43% ≤ CL<51%	340 ms
Active5 (5)	51% ≤ CL<59%	420 ms
Restrictive (6)	59% ≤ CL	460 ms

Table 3-5: Minimum packet distances in DCC variant B as a function of the DCC state as proposed in [2]

Furthermore the DCC paper [2] allows for message bursts for DP0 packets with 20 packets per seconds. The message burst should be not longer than 1 second within a 10 seconds interval. It is not clear how the DP0 packets are treated outside the burst. For the simulations in this document it is assumed that the DP0 packets are treated like DP1-DP3 packets. Hence, the distance to the last packet transmission has to meet the minimum distance defined in Table 3-5.

One example is shown below. It assumes that a DP3 packet (P_0) arrives prior to all other packets and can be directly forwarded to the EDCA queue of the MAC. Any later packet needs to wait for the minimum allowed transmission interval until it can be forwarded to the corresponding EDCA queue. Typically, the delay in the MAC caused by the CSMA procedure is significantly smaller than the minimum allowed transmission interval. In this case only one EDCA queue in the MAC layer contains a packet at the same time.

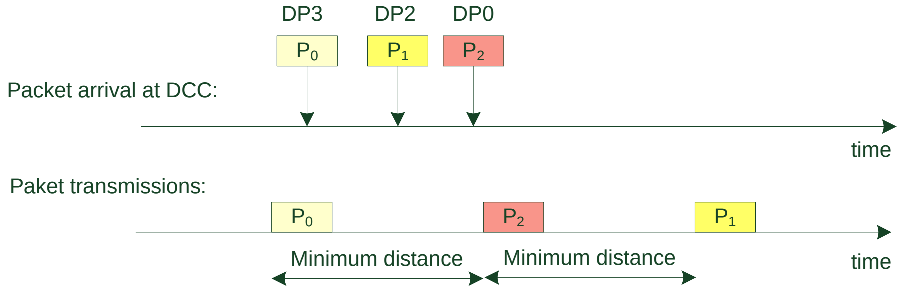


Figure 3-3: Example for the transmission of packets in DCC variant B outside the DP0 burst mode

It is important to notice, that in contrast to DCC variant A, CAMs might be delayed by the DCC in contradiction to the statement in section 1.4.1 of [2]. In the example above the arrival of the DP3 packet prior to the CAM causes a DCC delay of the CAM packet. The CAM generation cannot address this situation since it has no knowledge of other packets existing such as DENM generation and DENM forwarding. Further, DENM generation and DENM forwarding have not been designed to adhere to DCC. Forwarding is managed by the GeoNetworking protocol at the networking & transport layer and there are currently no mechanisms for informing higher layer about on-going forwarding. The example shows that the delay of the CAM can be even larger than the minimum allowed transmission interval. It assumes that a DP0 packet (P_3) arrives at the facilities layer shortly after the CAM packet (P_1) generation. Although the CAM generation is aware of the short packet distance, it is probably not reasonable to delay the DP0 packet. The facilities layer does not know if the DCC can still use the burst mode for parallel DP0 transmission. The same example with burst mode transmission would lead to the transmission sequence shown in Figure 3-4.

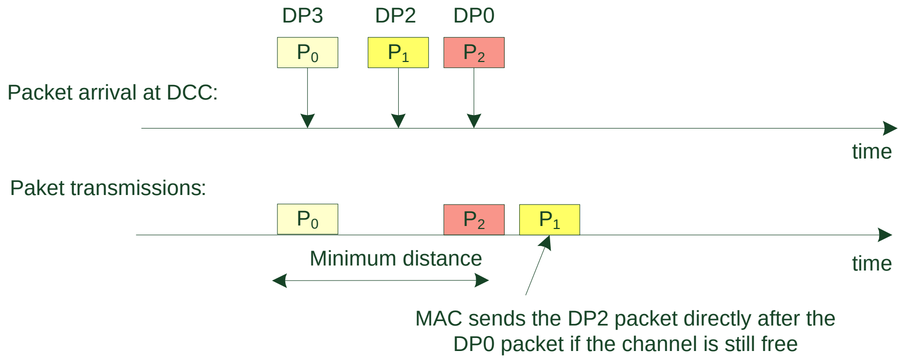


Figure 3-4: Example for the transmission of packets in DCC variant B inside the DP0 burst mode

It is assumed that a DP0 burst starts as soon as a DP0 packet arrives at the input of the DCC with

1. a time distance smaller than the minimum packet transmission interval to the last packet transmission and
2. no burst mode in the last 10 s

Although the facilities layer cannot guarantee that the generated CAMs are transmitted without DCC delay it seems to be reasonable to inform the facilities layer on the current minimum distance in the DCC. In any case it makes no sense to generate CAMs with shorter packet distance than T_{OFF}. As long as only CAMs are transmitted this still guarantees that the CAMs can be directly transmitted without delay.

3.3.4 DCC variant C

DCC variant C uses parts of DCC variant A, e.g., avoid delays in the DCC for CAM packets, and of DCC variant B, e.g., channel load thresholds. As for Variant A, separate transmission controls are foreseen for the three highest priority queues. They contain system and safety relevant information and should be transmitted without DCC delay. DCC variant C differs from DCC variant A by its treatment of DP3 packets. They are no longer sent independent of all other priority packet transmissions. In DCC variant C, DP3 packets will only be transmitted, if the distance to the last DP3 packet is larger than a minimum value (same as in DCC variant A) and the duty cycle within a measurement interval is below a certain threshold. Hence, an additional duty limitation is added, which avoids high peak duty cycles during DENM transmission phase, which might be a problem for cooperative ITS (C-ITS). The measurement interval will be set to 1 s according to the definitions in [10]. Note that the minimum time interval between DP3 packets is maintained to avoid that several DP3 packets are transmitted within short distance and increase the MAC delay for packet transmissions in the neighbourhood.

For all DCC states and the four priority levels a transmit power of 25 dBm is used. It will be shown later on that the channel load threshold of DCC variant A for DCC state Restrictive is unnecessary small, implying that many vehicles are in Restrictive state even for medium vehicle densities. Hence, DCC variant C will use the channel load thresholds of DCC variant B as shown in Table 3-6.

	Relaxed	**Active1**	**Active2**	**Active3**	**Active4**	**Active5**	**Restrictive**
Channel Load	[0%,19%[	[19%,27%[	[27%,35%[	[35%,43%[	[43%,51%[	[51%,59%[	≥59%
DP0	100 ms	100 ms	100 ms	100 ms	100 ms	100 ms	100 ms
DP1	100 ms	140 ms	180 ms	220 ms	260 ms	300 ms	340 ms
DP2	100 ms	140 ms	180 ms	220 ms	260 ms	300 ms	340 ms
DP3	100 ms	350 ms	600 ms	850 ms	1100 ms	1350 ms	1600 ms
DCmax	1%	0.9%	0.8%	0.7%	0.6%	0.5%	0.4%

Table 3-6: Minimum packet distances and the overall duty cycle limit in DCC variant C as a function of packet priority and DCC state

The packet distances are adapted accordingly, so that the behaviour of DCC variant C should be similar to DCC variant A. A comparison of the minimum packet distances for DCC variant A and C as a function of the channel load are shown below:

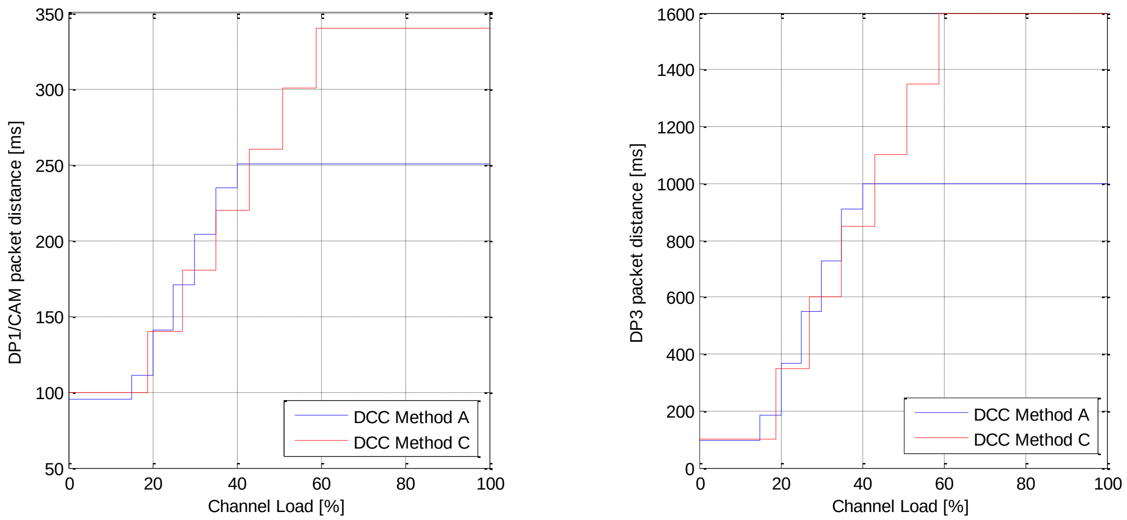


Figure 3-5: Comparison of TOFF as a function of channel load of DCC Method A and C for DP1 and CAM packets (left) and DP3 packets (right)

The performance of DCC variant C will be investigated in two steps. In a first step, no duty cycle limitations will be used for DP3 packets. In this case DCC variant C is identical to DCC variant A with the modified parameter set given in Table 3-6. This version will be denoted as “modified DCC variant A” and its performance will be compared to the original DCC variant A.

Then DCC variant C just adds a duty cycle limitation (see last row of Table 3-6) to the modified DCC variant A, which allows to analyse its impact on the number of transmitted packets, delays in MAC and DCC, collision rates, and the position error.

3.4 MAC layer

The DCC queues Q0 to Q3 containing the priority packets DP0 to DP3 are aligned with EDCA queues of priority AC_VO, AC_VI, AC_BE and AC_BK, respectively as defined in [5]. If there are packets in more than one EDCA queue, the packet with the highest priority is sent first.

Each EDCA queue has its own CSMA parameter set as summarized in Table 3-7. The arbitration interframe space (AIFS) is the minimum time between the end of one packet and the earliest transmission of the next packet and depends on the packet priority. It can be calculated from the slot time (SlotTime =13 µs) and the short interframe space (SIFSTime = 26 µs) according to

$$\text{AIFS[AC]} = \text{SIFSTime} + \text{AIFSN[AC]}\cdot\text{SlotTime}$$

DP class	AC	AIFSN	AIFS	CWmin	CWmax
DP0	AC_VO	2	58µs	3	7
DP1	AC_VI	3	71µs	7	15
DP2 (CAM)	AC_BK	6	110µs	15	1023
DP3	AC_BE	9	149µs	15	1023

Table 3-7: CSMA parameters (Part 1) [5]

The channel observation starts SIFSTime seconds after the end of the last packets. If the medium has been then idle for the following AIFSN[AC]·aSlotTime – aRxTxTurnaroundTime the next packet can be transmitted. In the simulation Rx/Tx switching time (aRxTxTurnaroundTime) is set to 2 µs which is the maximum value allowed for OFDM systems (see Table 18-17, [5]). This is a worst case assumption as the CSMA performance suffers from large switching time as any packet transmission starting within this interval cannot be detected anymore.

Parameter	Value
SlotTime	13 µs
SIFSTime	26 µs
aRxTxTurnaroundTime	2 µs
EDCA queue length	2

Table 3-8: CSMA parameters (Part 2) [5]

3.5 PHY layer

Packets are transmitted with a maximum power level of 25 dBm. The impact of the transmission channel on the packet reception success will be considered calculating the large scale fading parameters based on vehicle distances and shadowing in the Radio Channel Simulator (RCS). The small scale fading effect and the Doppler shift are taken into account using one of the defined ITS channel models (section 4.4 of the antenna white paper [6]):

1. Rural LOS
2. Highway LOS
3. Urban Approaching LOS
4. Crossing NLOS
5. Highway NLOS

	Tap 1	Tap 2	Tap 3		Units
Power	0	-14	-17		dB
Delay	0	83	183		ns
Doppler	0	492	-295		Hz
Profile	Static	HalfBT	HalfBT		

Table 3-9: C2C-G5 Rural LOS Parameters

	Tap 1	Tap 2	Tap 3	Tap 4	Units
Power	0	-10	-15	-20	dB
Delay	0	100	167	500	ns
Doppler	0	689	-492	886	Hz
Profile	Static	HalfBT	HalfBT	HalfBT	

Table 3-10: C2C-G5 Highway LOS Parameters

	Tap 1	Tap 2	Tap 3	Tap 4	Units
Power	0	-8	-10	-15	dB
Delay	0	117	183	333	ns
Doppler	0	236	-157	492	Hz
Profile	Static	HalfBT	HalfBT	HalfBT	

Table 3-11: C2C ITS-G5 Urban (Approaching) LOS Parameters

	Tap 1	Tap 2	Tap 3	Tap 4	Units
Power	0	-3	-5	-10	dB
Delay	0	267	400	533	ns
Doppler	0	295	-98	591	Hz
Profile	Static	HalfBT	HalfBT	HalfBT	

Table 3-12: C2C ITS-G5 Crossing NLOS Parameters

The packet error rates have been simulated in Matlab for a single channel receiver with standard packet detection and channel tracking based on data feedback. The results for a packet length of 1000 Octets and a data rate of 6 Mbps are shown in Figure 3-6.

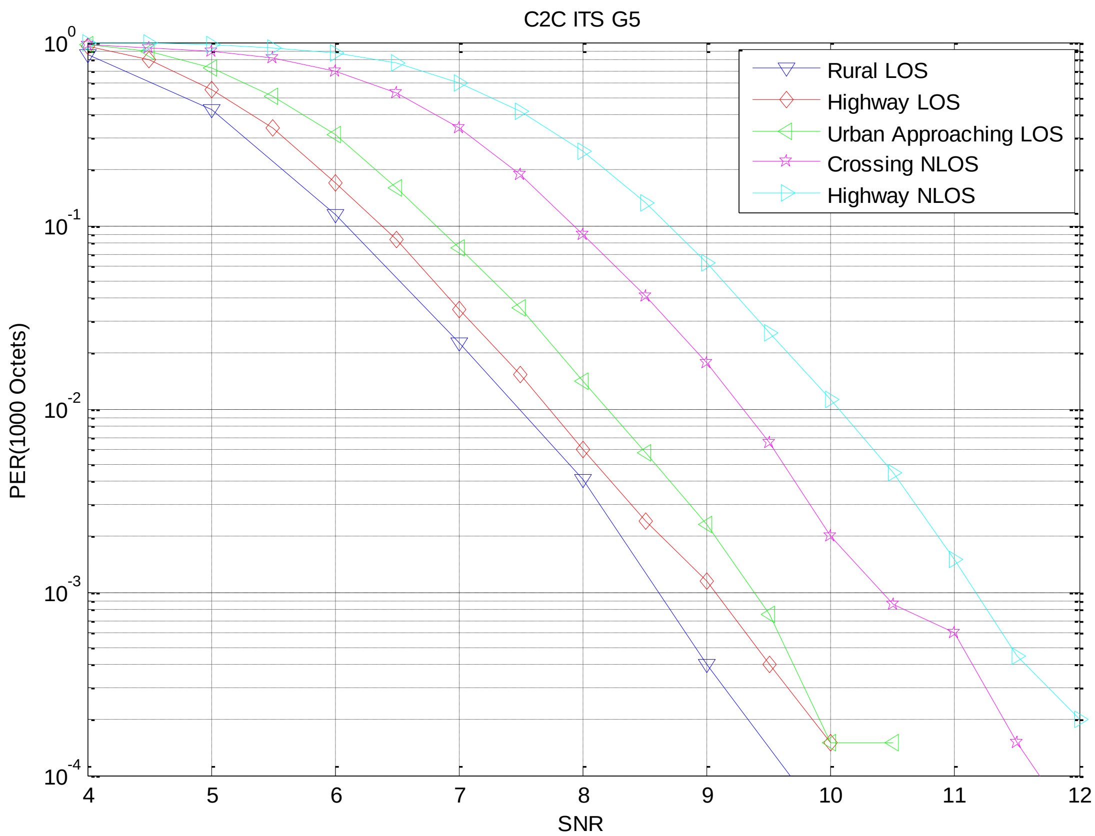


Figure 3-6: Packet error rate for 6Mbps and 1000 Octets

An additional noise figure of 6 dB is considered in the RLE when calculating the SNR at the input of the receiver baseband.

Besides packet transmission and reception the PHY is responsible for channel load estimation. The channel load is measured as described in section 1.3 of the DCC white paper [2]. Within each probing interval of 8 μs the average received signal level is compared to a signal threshold D-CCA of -85 dBm. In case the signal level exceeds the threshold a counter is increased by one. After 12500 probings the channel load is determined by the ratio of the counter divided by 12500.

$$CL = \frac{1}{N_p}\sum_{k=1}^{N_p}(P_{rx}(k) > -85\text{dBm}), \quad N_p = 12500$$

The channel load is then communicated to the DCC and the counter is reset to zero. Hence, the DCC access gets channel load updates in 100 ms intervals. In general, channel load estimations are subject to errors. The simulator can either assume perfect channel estimations (set PHYChannelLoadErr to false) or alternatively considers an error model as described in section 1.3.1 of the DCC white paper [2], which assumes a uniformly distributed measurement error in the range of ±2dB (set PHYChannelLoadErr to true).

The PHY parameters are summarized in Table 3-13

Parameter	Value
Maximum transmit power	25 dBm
Noise Figure	6 dB
Data Rate	6 Mbps
D-CCA	-85 dBm
CL Probing Interval	8 μs
CL Measuring Interval	100 ms
PHYChannelLoadErr	true or false

Table 3-13: PHY parameters

4 Radio Channel Simulator (RCS)

4.1 Simulation model overview

IMST RCS is the radio channel simulator used to derive the channel state information (CSI) used by RLE. In particular, it maps vehicle positions, velocities and orientations to channel state information for all inter-vehicle channels, given an environment and a vehicle configuration.

RCS features several simulation models. The model used for the present document is a simple box shaped vehicle model combined with a simplified vertical plane model including generic two-ray propagation with obstruction by vehicles. It has been selected according to the following guidelines:

- The simulation model should be most simple to facilitate reproducibility of results by a third party.
- The simulation model should be geared towards suitability for benchmarking purposes rather than utmost physical accuracy.
- The simulation model should incorporate the most important propagation effects, in particular:
    - ground reflection
    - obstruction of the line of sight by vehicles
    - different sizes of vehicles
- Due to the lack of standard recommended antenna patterns for vehicle-to-vehicle communications (the standardization process is ongoing), an isometric pattern with vertical polarization is to be used.

4.2 Environment model

Basic characteristics of the antenna model are:

- A global Cartesian coordinate frame is used.

The lane geometry of the highway was modelled according to the following source:
http://de.wikipedia.org/wiki/Richtlinien_f%C3%BCr_die_Anlage_von_Stra%C3%9Fen_%E2%80%93_Querschnitt

Parameter	Symbol	Value
Length of highway	lhw	2000 m
Number of Lanes	nl	8 (4 lanes each side)
Width of terrain each side	wt	10 m
Shoulder (Bankett)	ws	1.5 m
Emergency lane	we	2.5 m
Outer marginal strip	woms	0.5 m
Outer lane	wl0	3.5 m
Inner marginal strip	wims	0.75 m

Table 4-1: Highway model parameters

4.3 Vehicle model

4.3.1 Vehicle geometry and kinematics

Basic characteristics of the vehicle model are:

- With each vehicle, a vehicle fixed right-handed Cartesian coordinate frame is associated.
- The nominal position of the car defines the origin of the vehicle fixed coordinate frame.
- The vehicle fixed coordinate frame is oriented such that the X-axis corresponds to the driving direction, and the Z-axis facing upstream.
- The orientation of a vehicle is defined by Euler angles that define the orientation of the coordinate axes of the vehicle fixed frame with respect to the global coordinate frame (see below).
- The nominal position, velocity, and orientation of each vehicle are determined by a separate traffic model.
- The shape of each vehicle is described by a box.
- With each vehicle, a vehicle car model is associated. The box dimensions are a function of the vehicle's car model (see below).

The following vehicle car models and box sizes have been used:

Vehicle car model	Description
SCAR	Small closed car
CCAR	Small cabriolet
MST	Medium sized (transporter)
C	Coach

Table 4-2: Vehicle car models

Vehicle car model	x_{min}	y_{min}	z_{min}	x_{max}	y_{max}	z_{max}
SCAR	-2.125	-1.00	0.00	2.125	1.00	1.40
CCAR	-2.120	-1.00	0.00	2.12	1.00	1.30
MST	-2.300	-1.00	0.00	2.300	1.00	1.90
C	-4.200	-1.00	0.00	4.200	1.00	2.80

Table 4-3: Vehicle sizes

The models have been simplified as boxes in order to reduce the computational complexity, whereby the dimensions of each box (L x W x H) are similar to those of the corresponding detailed and dimensioned car model (e.g. from an STL (Surface Tesselation Language) model). An example for a detailed STL model and its simplified representation are shown for an SCAR (VW Scirocco) in Figure 4-1 and Figure 4-2 respectively.

The orientation of a vehicle is defined using Euler angles as follows. A global coordinate vector can be transformed to the vehicle fixed frame using the transformation matrix $\boldsymbol{R} = \boldsymbol{R_1}(\rho_V)\boldsymbol{R_2}(\nu_V)\boldsymbol{R_3}(\alpha_V)$ (see [11] for the definition of the rotation matrices), where ρ_V, ν_V, α_V are the roll, pitch and azimuth angle of the vehicle under consideration w.r.t. the global coordinate frame, respectively.

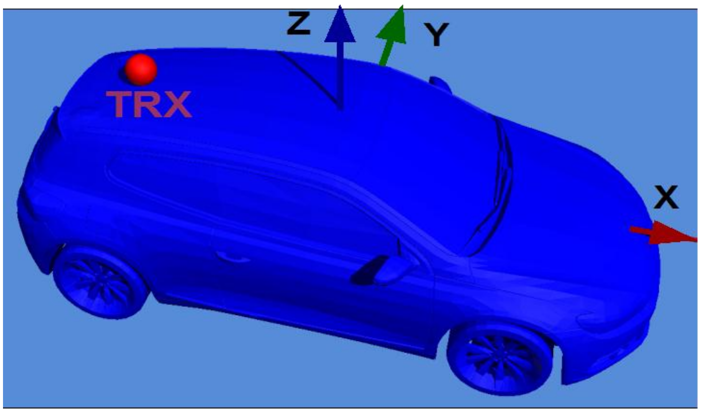


Figure 4-1: Detailed and dimensioned car (VW-Scirocco) model from an STL model.

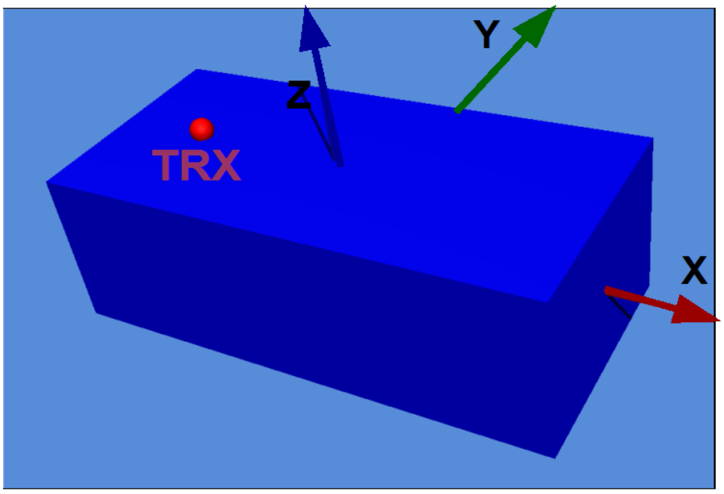


Figure 4-2: Simplified box-car-model for VW-Scirocco (L x W x H) = (4.25 x 2.0 x 1.4) m.

4.3.2 Antenna model

Basic characteristics of the antenna model are:

- With each antenna, an antenna fixed right-handed Cartesian coordinate frame (AFCF) is associated.
- For the current simulation, the number of antennas per vehicle has been limited to one (Single Input Single Output (SISO) case).
- The antenna is positioned on the roof of the vehicle.
- The antenna position is described by its Vehicle Fixed Coordinate Frame (VFCF) coordinates.
- The antenna orientation is described by Euler angles (α, ν, ρ) of the antenna relative to the VFCF.
- Each antenna is considered to act both as transmitter (Tx) and receiver (Rx).
- For the current simulation, an isotropic antenna pattern has been assumed.

The transformation from VFCF to the antenna fixed coordinate system is accomplished by the rotation matrix $R = R_1(\rho_A)R_2(\nu_A)R_3(\alpha_A)$, where ρ_A, ν_A, α_A are the roll, pitch and azimuth angle of the antenna w.r.t. the vehicle fixed coordinate frame, respectively. Due to the use of isotropic patterns for the current investigation, the transformation is trivial.

Vehicle car model	Antenna position	x_A	y_A	z_A	α	ν	ρ
SCAR	roof	-1.28	0	1.5	0	0	0
CCAR	roof	-2	0	1.4	0	0	0
MST	roof	-2.05	0	2	0	0	0
C	roof	-3.9	0	2.9	0	0	0

Table 4-4: Antenna position in vehicle fixed frame (in m) and Euler angles (in degree)

4.4 Propagation model

Basic characteristics of the propagation model are:

- The model is memoryless (instantaneous CSI is independent of on any earlier state).
- The path loss expectation between two vehicles (antennas) is determined using a two-ray model in the vertical plane between both antennas.
- For the two-ray model, a *generic* ground reflection coefficient of -0.3 is used.
- Small-scale fading is modelled using ITS G5 models (see section 3.5).
- For each obstruction of the direct path between two antennas by another vehicle, an additional attenuation proportional to the direct path length inside the obstructing vehicle (considering its position and orientation) is added. The additional attenuation is given by the parameter L_O (in dB/m).
- The Doppler shift is derived from the velocity vectors of the Tx and Rx vehicles.
- Any effect of an obstructing vehicle on the Doppler shift is neglected.
- The delay spread is estimated by a simple heuristic; in particular, for each obstruction the delay spread estimate is incremented by a fixed amount.

In particular, for any two different vehicles (more precisely, for the associated antenna feeds), the model estimates the following quantities:

Symbol	Description
PL	Path loss
f_D	Doppler shift
σ_{rms}	r.m.s. delay spread

Table 4-5: Propagation model output

The delay spread is used to select in between LOS and NLOS ITS model. For any delay spread greater than zero the NLOS model is used. The Doppler shift is neglected as its effect is already considered in the ITS model. The following input parameters are used:

Symbol	Value	Description
K	128, 256, 512	Number of vehicles
M_k	$M_k \in \{\mathrm{SCAR}, \mathrm{MCAR}, \mathrm{MST}, \mathrm{C}\}$	Car model of the k-th vehicle
$(x_{min}, x_{max}, y_{min}, y_{max}, z_{min}, z_{max})_k$	(cf. Table 4-2)	Dimensions of the k-th vehicle box w.r.t. to the vehicle fixed coordinate system. These quantities are defined by the vehicle car model M_k.
$(x_A, y_A, z_A, \alpha_A, \nu_A, \rho_A)_k$	(cf. Table 4-4)	Nominal antenna position and orientation of the antenna of the k-th vehicle w.r.t. to the vehicle fixed coordinate system
$(x_V, y_V, z_V, u_V, v_V, w_V, \alpha_V, \nu_V, \rho_V)_k$	(generated by traffic model)	Instantaneous position, velocity, and orientation of the k-th vehicle
L_O	1 dB/m	Additional attenuation by obstruction
r_g	-0.3	Ground reflection coefficient

Table 4-6: Propagation model input parameters

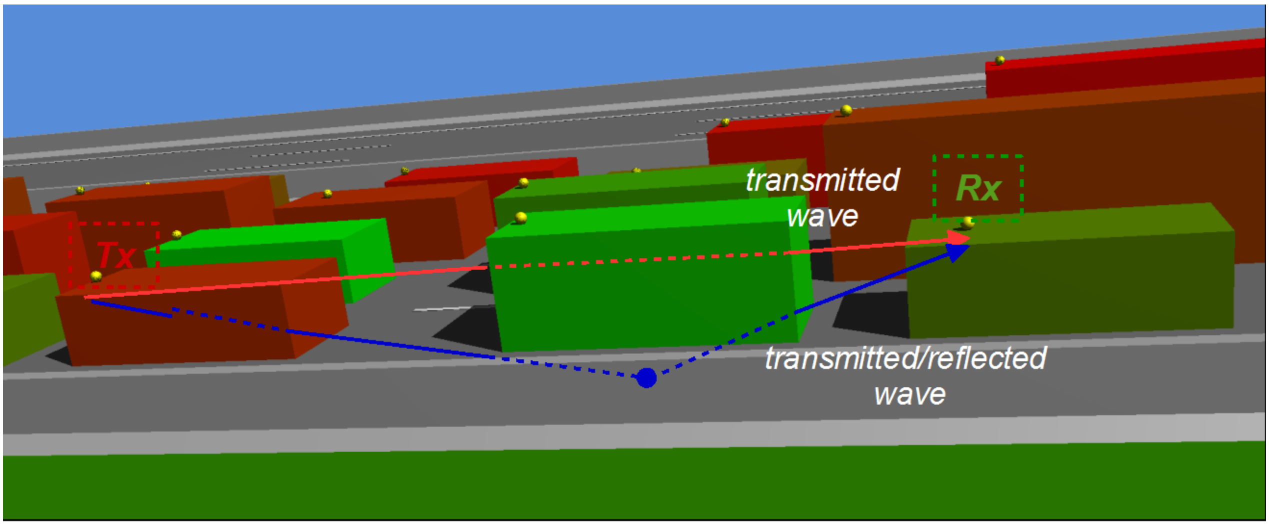


Figure 4-3: Obstructed line-of-sight scenario: direct path ray transmitted (through obstructing vehicle between Tx and Rx) and a ground reflected ray. Yellow spheres mark antenna positions.

5 DCC performance

5.1 DCC state transitions

5.1.1 Target

This section analyses the impact of the timing parameter settings (NDL_TimeUp, $NDL\_TimeDown$) described in section 3.3.1 on the DCC state adaptation and system performance. Simulations are performed in a highway scenario with only CAM transmissions during the first 20 seconds (see [3], section 2.1) followed by an accident in the middle of the simulated highway section in the upstream direction resulting in a fast increase of the channel load due to DENM transmissions as shown below. Two different ITS models are used for packet error calculations. In case there is a LOS connection between the considered transmitter / receiver pair the Highway LOS model is used, otherwise Highway NLOS. The performance will be compared for perfect channel load estimations and with a channel load estimation error which is equally distributed within ±2dB as described at the end of section 3.5. Channel load smoothing as described in section 3.3.1 is always activated in the DCC.

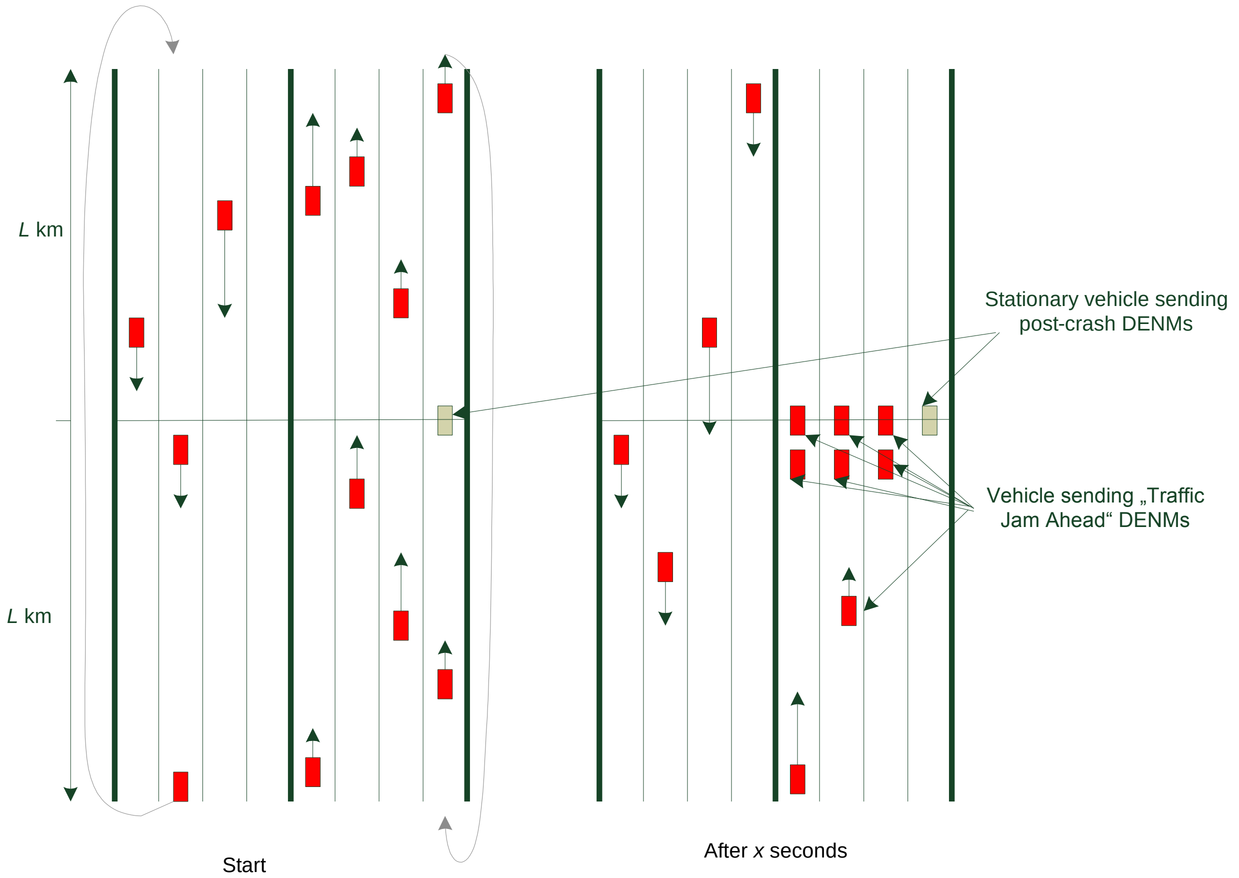


Figure 5-1: Scenario (Highway with accident and traffic jam)

5.1.2 Parameter settings

The results presented in this section are based on a highway scenario with 128 vehicles using DCC variant A. The same analysis has been repeated for DCC variant B as well as higher vehicles densities, but the conclusions are the same and therefore not presented here. The following settings are used for the two timing parameters, which trigger the transition to a more restrictive NDL_TimeUp and a less restrictive DCC state ($NDL\_TimeDown$):

NDL_TimeUp	$NDL\_TimeDown$
1000 ms (default)	5000 ms (default)
600 ms	3000 ms
200 ms	1000 ms

Table 5-1: Timing parameter settings, ETSI TS 102 687 [2]

5.1.3 Simulation results

Simulation output data are obtained for all vehicles in the simulation. Wherever reasonable, one or more vehicles are exemplarily selected to show their specific behaviour over time. Figure 5-2 for example shows the positions and velocity of vehicle ID 2 during the simulation time of 100 s. This car starts at position 1669 m and travels with a velocity of 110 km/h in the upstream direction. When the accident happens after 20 seconds, the vehicle has already left the highway section and re-entered it with a randomly selected velocity of 114 km/h. At 20 s it is located at x position 290 m. It continues travelling with constant speed up to position 498 m and then starts braking while approaching the crashed car. After 47.8 seconds the velocity is reduced to zero and the vehicle stops at position 968 m within the traffic jam.

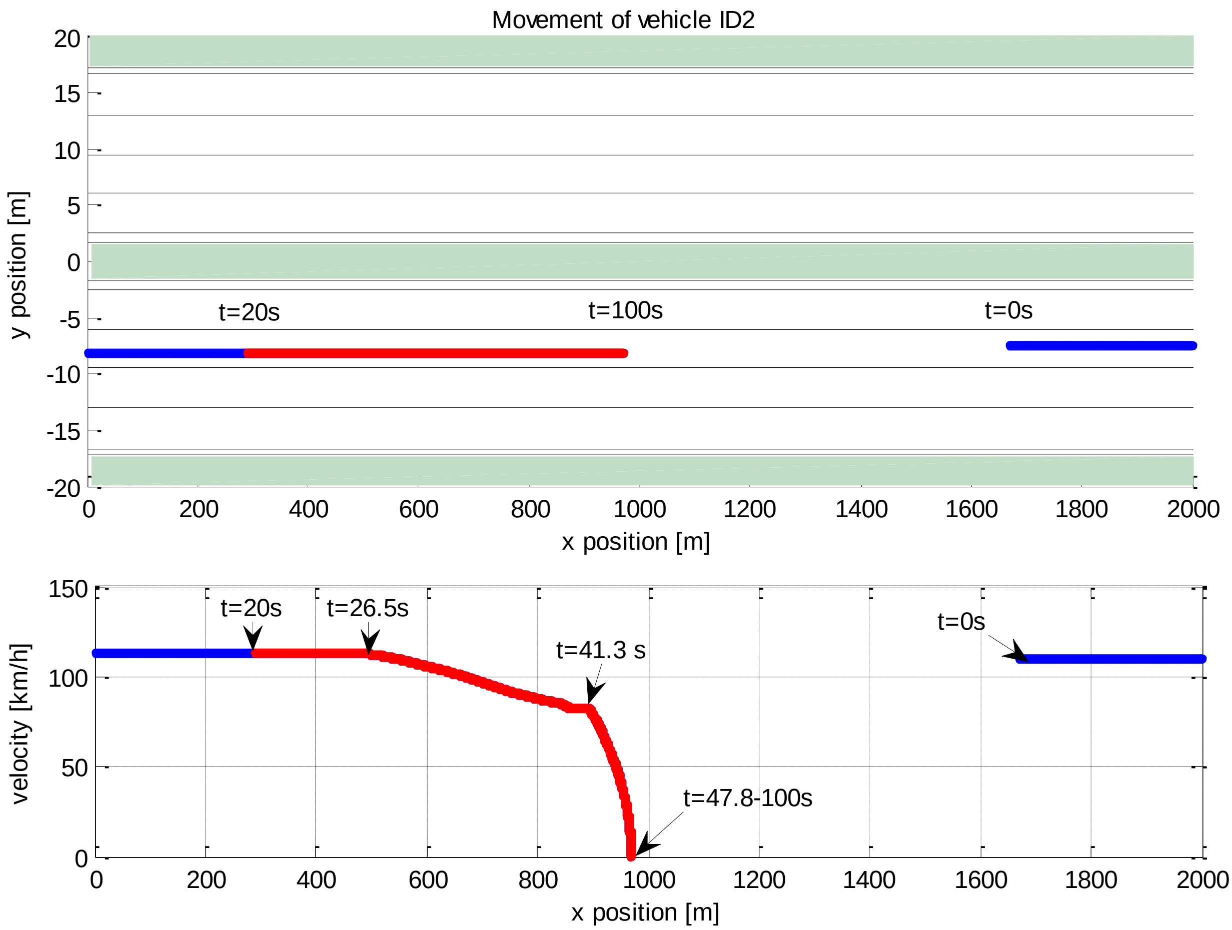


Figure 5-2: Movement of vehicle ID2 in highway scenario with 128 vehicles

The transmitted DP1, CAM and DP3 of vehicle ID2 are shown in the upper plot of Figure 5-3. Due to the high velocity during the first 20 seconds, CAMs (blue dots) are transmitted often (e.g., at a speed of 100 km/h the CAM generation rules mandate ~7Hz). After the stop at 47.8 seconds the CAM transmit interval becomes 1000 ms. The first DP1 packets (red dots) indicating a traffic jam ahead are transmitted at the end of the braking operation as soon as the velocity drops below 30 km/h. According to the triggering conditions they are repeated for 20 seconds with a 500 ms repetition interval (section 2.1.2.1 in [3]).

The received packets are shown in the lower plot in Figure 5-3. Prior to the own DP1 transmissions the vehicle has received DP1 packets from the crashed vehicle and DP1 as well as DP3 packets from other neighbours closer to the crashed car. Hence, the own transmission of DP3 packets starts prior to the first DP1 transmission.

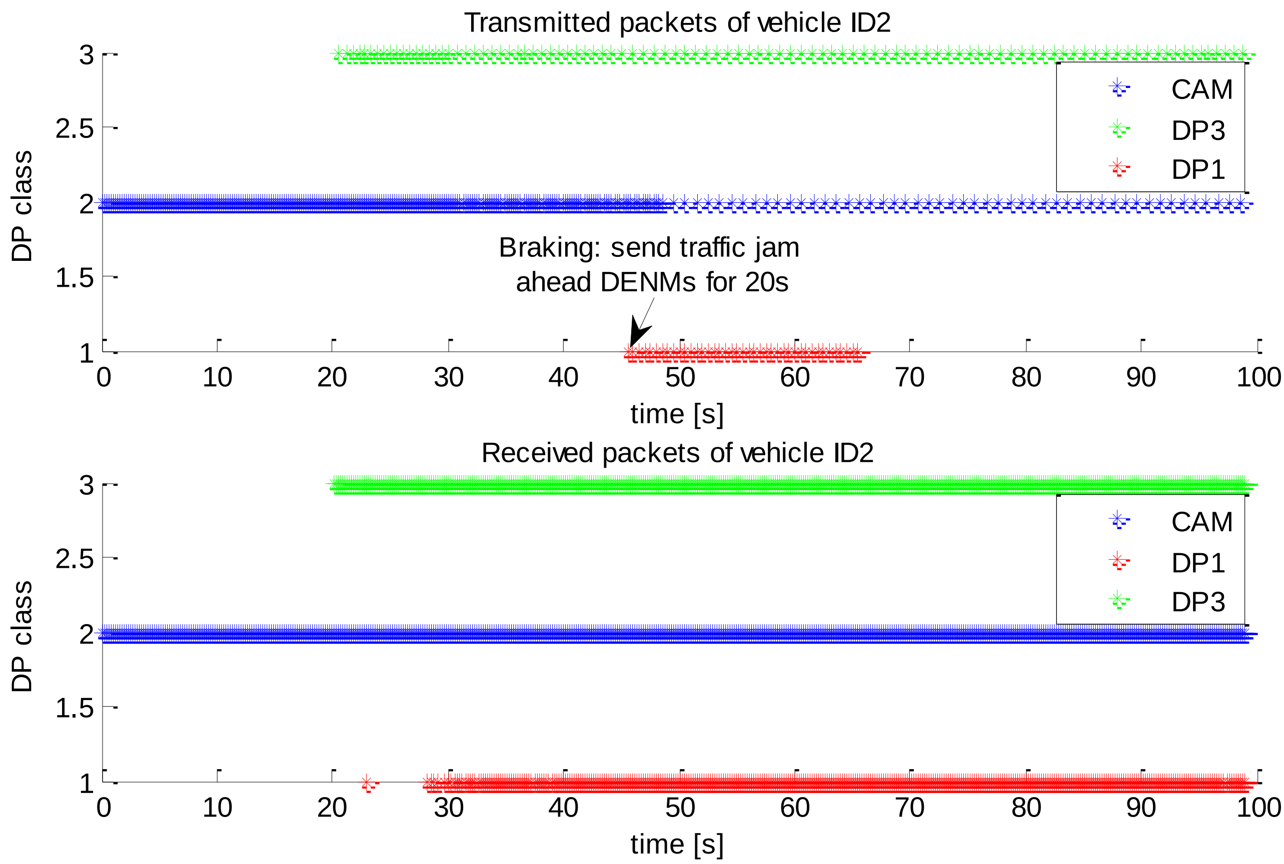


Figure 5-3: Transmitted and received DP1, CAM and DP3 packets of vehicle ID2

As shown above, packet transmissions tend to be periodic. The triggering conditions foresee DP1 packet repetitions with equal time offsets (see green dots in the upper plot of Figure 5-3) and the number of DP3 transmission requests is typically so high that they are sent with exactly the minimum packet interval specified by the DCC. The periodic nature of packet transmissions may results in a time varying channel load as soon as the packet distances are larger than the channel load measuring interval. Figure 5-4 shows as an example the number of received DP1 and DP3 packets within 100 ms measuring intervals for vehicle with ID2.

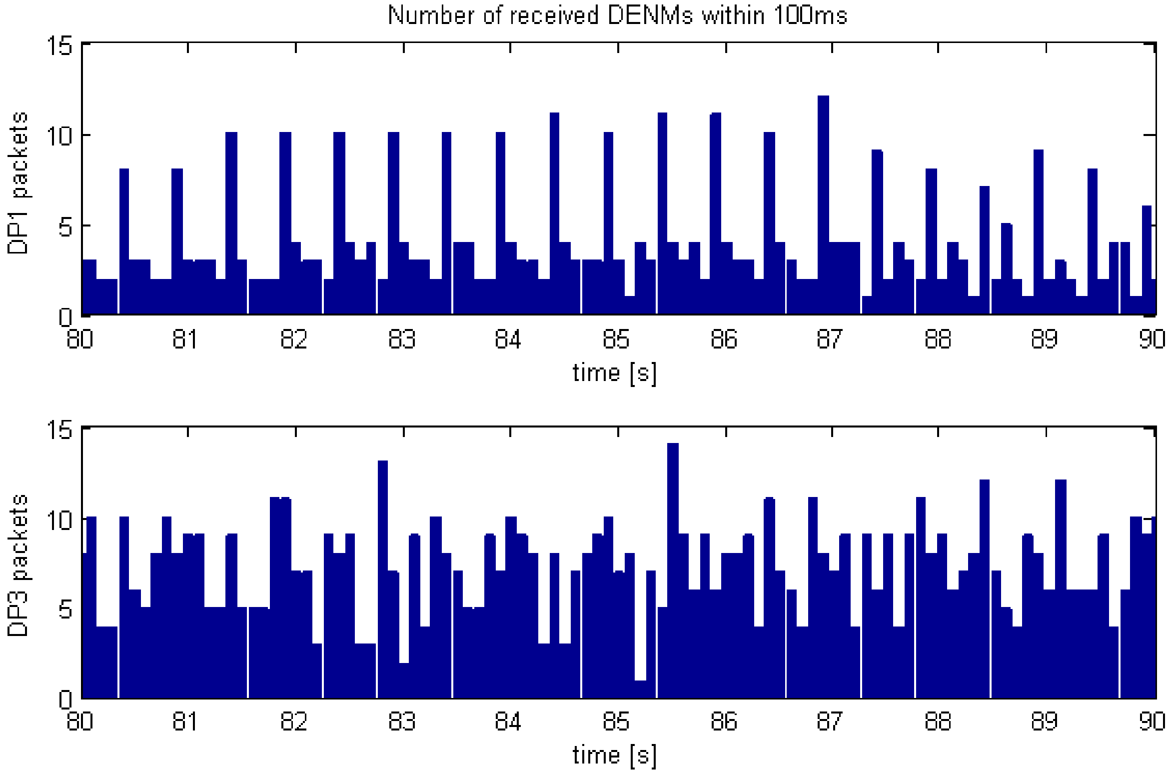


Figure 5-4: Periodicity of the number received DP1and DP3 of vehicle ID2

Hence, the algorithm for DCC state adaption will have to cope with the channel load fluctuations, which might suggest using larger time constants for up- and down ramping. On the other side, there will be a sudden increase of DP1 and DP3 after the crash resulting in fast channel load increase.

The influence of the timing constants on the DCC state transitions are shown in the figures below. The first parameter set uses the default parameters with 1 s for NDL_TimeUp and 5 s for $NDL\_TimeDown$. The resulting DCC state and the measured channel load are shown in Figure 5-5 for vehicle ID2 without (left) and with (right) measurement errors.

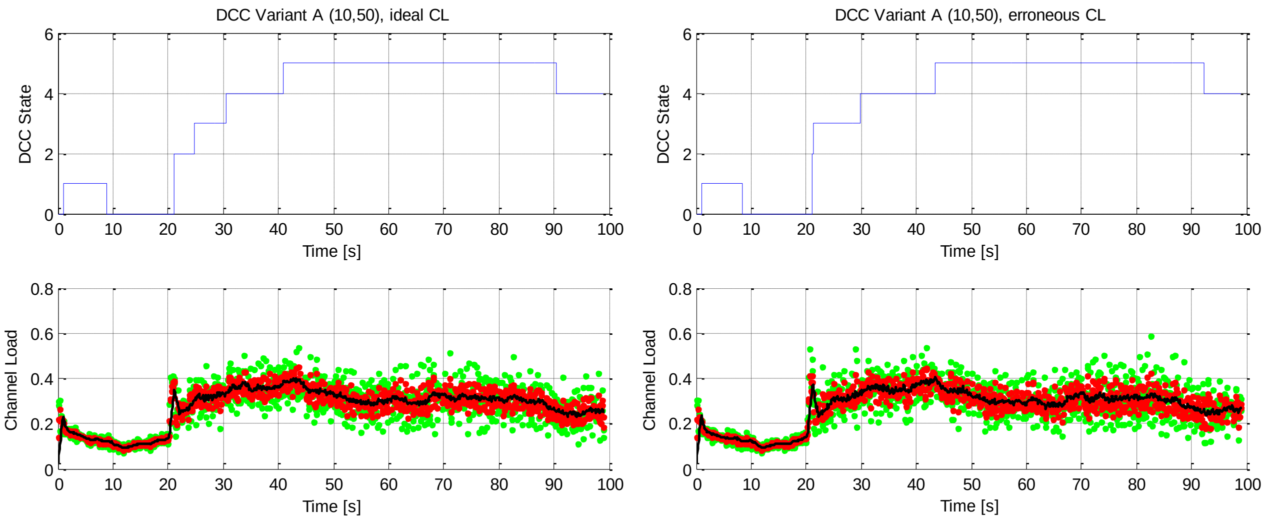


Figure 5-5: DCC state adaptation and measured channel load of vehicle ID2 for DCC variant A with NDL_TimeUp =1s, $NDL\_TimeDown$ =5s

The figure on the left side assumes perfect channel estimation. The DCC state starts from *Relaxed* (0) and quickly changes to *Active1*, as the channel load caused by the CAM transmissions is only slightly below 20%. Then the vehicle moves towards the end of the simulated highway section, where the channel load slightly decreases due to a lower number of neighbours and the DCC state changes from *Active*1 back to *Relaxed*. Then after 20 seconds, a significant increase of the channel load is observed, which is caused by the start of the DP1 and DP3 packet transmissions after the crash. The DCC state adapts after NDL_TimeUp to *Active2* (2). As the vehicle continuous moving in the direction of the traffic jam, the number of received DP1 and DP3 furthermore increases so that the DCC state increases to *Active5* (5). This state is maintained quite a long time, before the state reduces to *Active4* (4) at the end simulation.

A similar behaviour is observed if channel load measurement errors are considered. The measured and filtered channel loads are only slightly higher right after the crash, so that the state changes directly from *Relaxed* to *Active3* (3). Nevertheless the filtered channel load is almost identical after channel load smoothing and the impact of channel load measurement errors seems to be almost negligible. In general the number of state changes is reasonably small due to the large time constants for state increase or decrease, which makes it difficult for the DCC state to change.

Channel state adaptations are expected to be faster using smaller time constants. Results for timing parameters of NDL_TimeUp =0.6s, $NDL\_TimeDown$ =3s are shown in Figure 5-6, while Figure 5-7 presents the results for NDL_TimeUp =0.2s, $NDL\_TimeDown$ =1.0s.

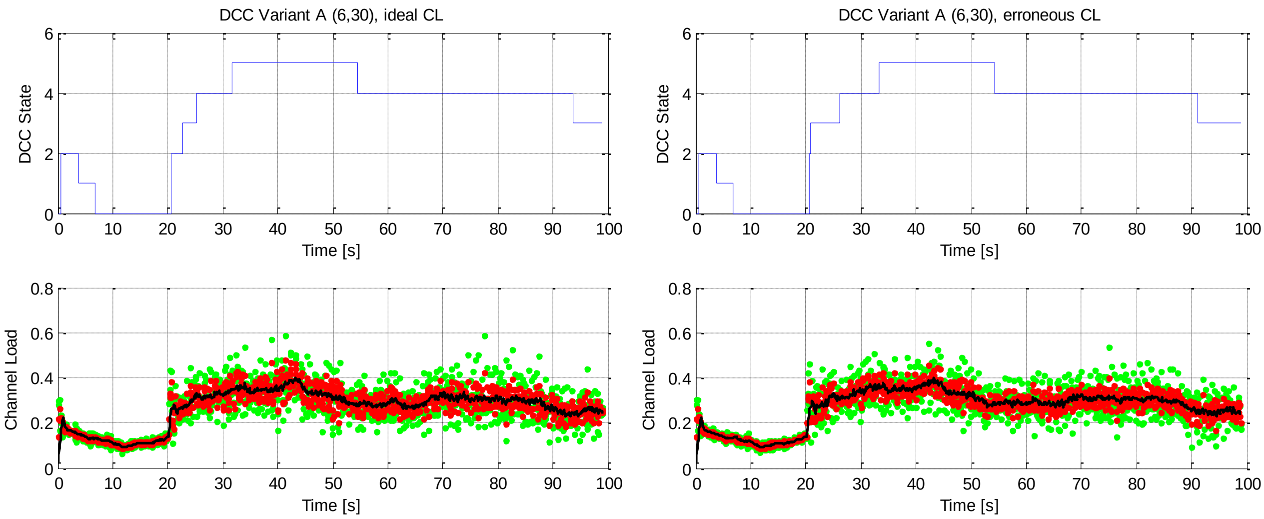


Figure 5-6: DCC state adaptation and measured channel load of vehicle ID2 for DCC variant A with NDL_TimeUp =0.6s, $NDL\_TimeDown$ =3s

As expected, the time for DCC state adaptation right after the start of the DENM transmissions reduces and channel states adapt more frequently. Again, there is almost no difference between the behaviour with and without perfect channel load measurements.

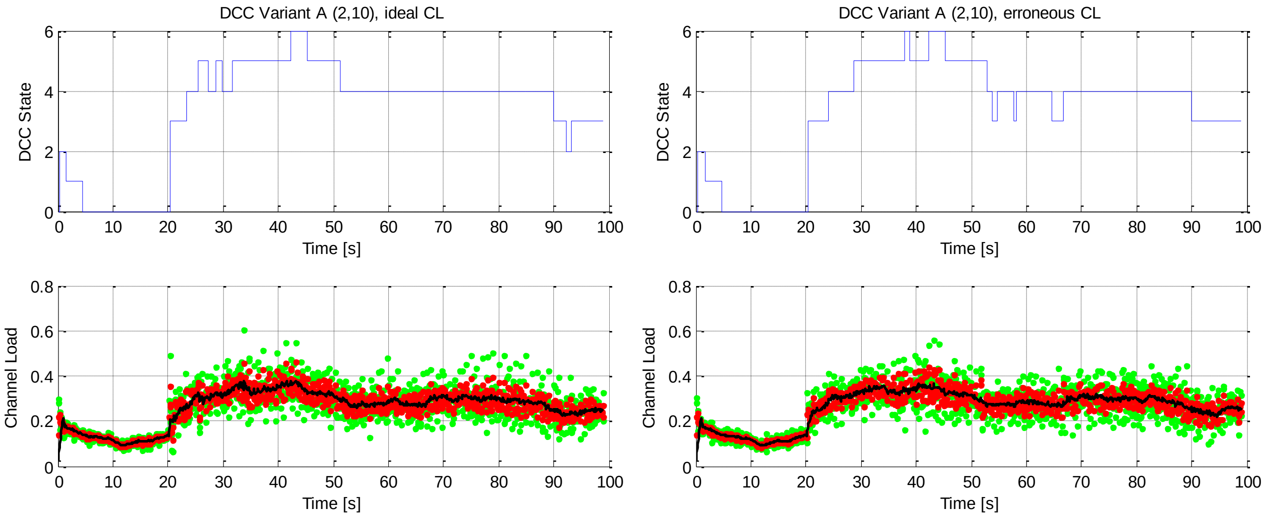


Figure 5-7: DCC state adaptation and measured channel load of vehicle ID2 for DCC variant A with NDL_TimeUp =0.2s, $NDL\_TimeDown$ =1.0s

A quite high number of state changes can be observed in the simulations with the smallest time constants in Figure 5-7. As the facilities layer needs to be informed on the minimum time interval each time the DCC state changes, there should be a good reason to use such small timing constants.

In order to analyze the influence of the channel state adaptation on the system performance, information for all transmitted and received packets are stored for each simulation run, so that the following parameters can be calculated:

TxRequest:	Number of transmit requests at the DCC input within simulation time averaged over all vehicles
TxPacket:	Number of transmitted packets within simulation time averaged over all vehicles
RxPacket:	Number of received packets within simulation time averaged over all vehicles
$\bar{d}_{DCC}$	Mean packet delay [s] in the DCC layer averaged over all vehicles
$std(d_{DCC})$	Standard deviation of the packet delay [s] in the DCC
$\hat{d}_{DCC}$	Maximum packet delay [s] in the DCC layer averaged over all vehicles
$\bar{d}_{MAC}$	Mean packet delay [ms] in the MAC layer averaged over all vehicles
$std(d_{MAC})$	Standard deviation of the packet delay [ms] in the DCC
$\hat{d}_{MAC}$	Maximum packet delay [ms] in the MAC layer averaged over all vehicles

The results for DP1 packets are summarized in Table 5-2.

DP1	1.0/5.0 ideal	1.0/5.0 error	0.6/3.0 ideal	0.6/3.0 error	0.2/1.0 ideal	0.2/1.0 error
TxRequest	19.2	19.2	19.2	19.2	19.2	19.2
TxPacket	19.2	19.2	19.2	19.2	19.2	19.2
RxPacket	1479	1468	1461	1475	1460	1454
$\bar{d}_{DCC}$[s]	0	0	0	0	0	0
$std(d_{DCC})$ $[s]$	0	0	0	0	0	0
$\hat{d}_{DCC}$[s]	0	0	0	0	0	0
$\bar{d}_{MAC}[\mathrm{ms}]$	0.30	0.31	0.29	0.29	0.30	0.32
$std(d_{MAC})$[ms]	0.38	0.37	0.37	0.37	0.38	0.39
$\hat{d}_{MAC}[\mathrm{ms}]$	1.53	1.50	1.58	1.58	1.60	1.61

Table 5-2: DCC variant A, 128 vehicles, DP1 packets

Each vehicle receives on average 19.2 DP1 transmit requests within 100 s simulation time. This number is slightly smaller than the maximum value, which can be calculated as follows:

- 64 vehicles in downstream direction do not transmit any DP1 packets
- 63 vehicles in upstream directions transmit 41 DP1 (traffic jam ahead) packets
- 1 vehicle transmits 61 DP1 (stationary vehicle warning) packets

$$TxRequest_{max} = \frac{63 \cdot 41 + 61}{128} = 20.66$$

The number of transmitted DP1 packets per vehicle is shown in Figure 5-8, where DP1 packets are indicated by the red bars in the middle of the plot. The majority of the vehicles travelling in the upstream direction as well as the crashed car with ID0 have already sent their DP1 packets. Only a few of them (e.g. ID3) have just arrived at the end of the traffic jam within 100 s simulation time and there was not sufficient time to send all the repetitions.

As shown in Table 5-2 all DP1 transmit requests result in a packet transmission with no delay in the DCC layer as the inter packet distances defined by the triggering conditions are always larger than the minimum packet distance required by the DCC. There is an average CSMA delay in the MAC of 0.29 ms to 0.32 ms and an average maximum delay of 1.50 ms to 1.61 ms. Only small variations for the different timing parameters with and without error model for the channel load measurements are observed.

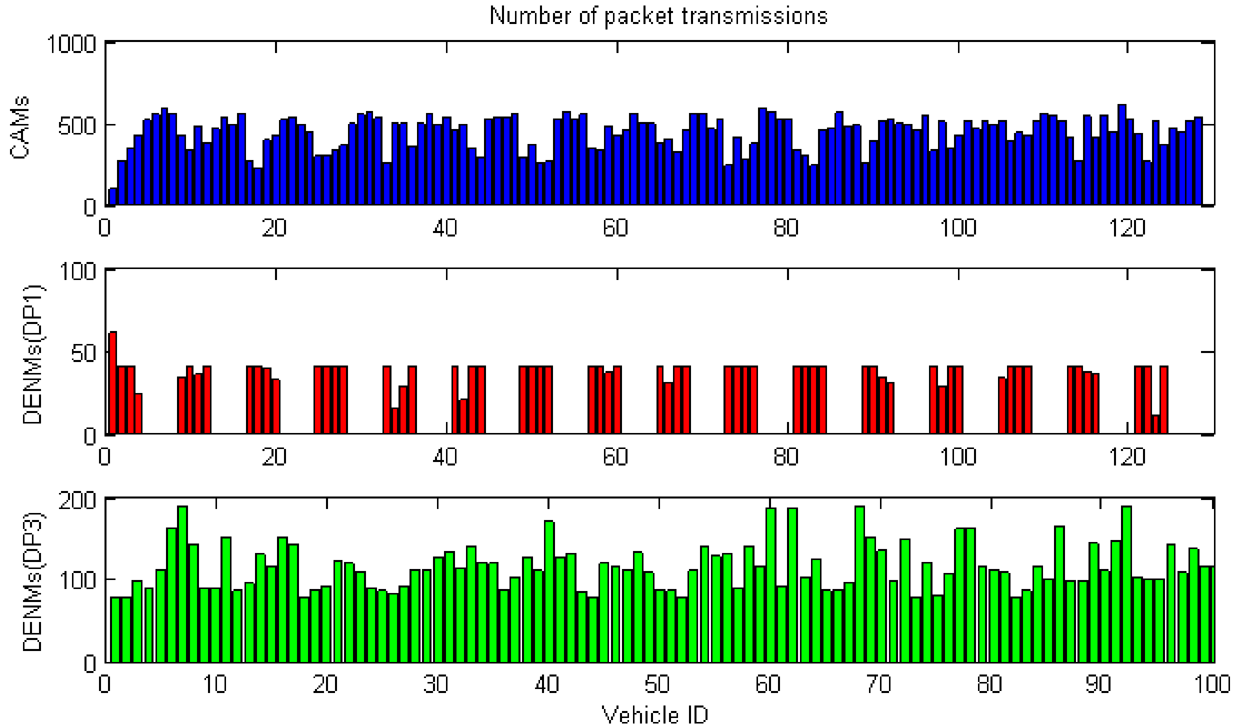


Figure 5-8: Number of transmitted packets as a function of priority, DCC variant A, 128 vehicles

The same is true for CAM and DP3 packet transmissions and reception as shown in Table 5-3 and Table 5-4, respectively.

CAM	**1.0/5.0 ideal**	**1.0/5.0 error**	**0.6/3.0 ideal**	**0.6/3.0 error**	**0.2/1.0 ideal**	**0.22/1.0 error**
TxRequest	444.8	445.8	445.9	447.1	442.2	443.3
TxPacket	444.8	445.8	445.9	447.1	442.2	443.3
RxPacket	30166	30299	30047	30252	29902	30058
$\bar{d}_{DCC}$[s]	0	0	0	0	0	0
$std(d_{DCC})$ [s]	0	0	0	0	0	0
$\hat{d}_{DCC}$[s]	0	0	0	0	0	0
$\bar{d}_{MAC}$[ms]	0.61	0.62	0.61	0.60	0.58	0.59
$std(d_{MAC})$ [ms]	0.95	0.95	0.98	0.93	0.92	0.92
$\hat{d}_{MAC}$[ms]	6.83	7.20	7.81	6.75	6.87	6.91

Table 5-3: DCC variant A, 128 vehicles, CAM packets

DP3	1.0/5.0 ideal	1.0/5.0 error	0.6/3.0 ideal	0.6/3.0 error	0.2/1.0 ideal	0.22/1.0 error
TxRequest	4553.5	4568.3	4565.8	4525.8	4503.1	4453.8
TxPacket	112.8	111.9	114.4	114.7	114.6	114.9
RxPacket	5881	5796	5723	5708	5529	5486
$\bar{d}_{DCC}$[s]	0.11	0.11	0.11	0.12	0.12	0.12
$std(d_{DCC})\ [s]$	0.12	0.12	0.13	0.14	0.13	0.12
$\hat{d}_{DCC}$[s]	0.87	0.91	0.96	1.01	0.88	0.83
$\bar{d}_{MAC}$[ms]	1.10	1.07	1.03	1.03	0.96	1.04
$std(d_{MAC})\ [\mathrm{ms}]$	1.62	1.58	1.74	1.50	1.41	1.64
$\hat{d}_{MAC}$[ms]	9.70	9.22	11.86	8.67	8.21	10.40

Table 5-4: DCC variant A, 128 vehicles, DP3 packets

There is one interesting point to note looking at the number of transmit requests and actually transmitted packets for DP3 packets. There are more than 4500 DP3 transmit requests per vehicle, but the number of actually transmitted DP3 packets is significantly smaller due to the DCC limitations. Hence, DP3 packets are the only ones which need to be stored in the corresponding DCC queue. In the simulations, the DCC queue may hold up to 5 packets, which is not sufficient to store all transmit requests. In case of a buffer overflow the oldest packet is skipped and the new one enters the queue. This strategy minimizes the delay in the DCC, as the DCC queue always contains the most recent packets. In the simulations the oldest packet within the queue is transmitted first, which results in the smallest standard deviation for the DCC delay.

Summary:

- The impact of noisy channel measurements seems to be small, as channel load variations especially during the DENM transmission phase are already quite large even for perfect measurements.
- There is a slightly higher peak channel load right after the crash for the high timing constants, but the impact of timing parameter settings on the system performance is small. Hence the advantages of a faster state adaptation are not significant.
- Smaller timing parameters result in a higher number of DCC state changes. Each state change requires a modification of the minimum packet distance, which needs to be communicated to the facilities layer. Hence, small timing parameters should not be used.
- The channel load is already in between 30% and 40% with only 128 vehicles on a 2 km highway section after the accident.
- The number of DP3 transmit requests is by a factor of **40** higher than the number of transmitted DP3 packets in all realizations. Hence, DCC regulation is already reducing the channel load and will be required even for small vehicle densities to cope with the extensive packet forwarding of DENMs by the GeoNetworking protocol.

Side note with regards to the high number of DP3 requests:

DP1/DP3 packets are forwarded if the receiving node is within the relevance area. The relevance area of “traffic jam ahead” messages is a cycle of 1000m radius, while the “post crash” messages have a relevance area with a radius of 5000 m. Hence, most of the receiving vehicles are in the relevance area and packets are forwarded 9 times (10 hops). A number of DP3 packet transmissions are skipped due to duplicate packet detection of the contention-based forwarding algorithm, but not all. If a packet is received by vehicles with a similar distance (and there are many within the traffic jam), the calculated time offsets in the forwarding algorithm of the GeoNetworking protocol are quite similar. They depend on the distance to the transmitter and a 10 m difference in distance results in an additional offset of only 1 ms. Duplicate packet detection requires that the earlier packet is received properly in order to skip the transmissions in the second vehicle. Let us assume that two vehicles receive the same DP1 or DP3 packet and schedule their DP3 forwards at time T1 and T2. The difference abs(T1-T2) must be larger than the DP3 packet length plus possible variations in DCC and MAC delay to allow for duplicate packet detection. Otherwise both vehicles forward the received packet. We have not analyzed the performance of the forwarding algorithm, but we can see from GeoNetworking layer debug file, that often more than one vehicle forwards the packet.

Additionally, the number of DP3 transmissions could be significantly reduced with a proper definition of the relevance area. Traffic jam warnings for example only need to be forwarded to those cars approaching the traffic jam. The use case developer should be aware that the relevance area of the use case needs to be properly defined.

5.2 Comparison of DCC variants

5.2.1 Target

This section compares the performance of three different DCC variants described in section 3.3 using the highway scenario with an accident after 20 s. Three different numbers of vehicle will be considered, i.e. 128, 256, and 512. The timing constant for DCC state up- und down ramping will be set to the default values of 1 s for a state increase and 5 s for a state decrease. The following parameters will be investigated and compared:

Transmit and receive statistics:

- Total number of transmission requests arriving at the DCC layer as a function of priority averaged over all vehicles in the simulation
- Total number of transmitted packets as a function of priority averaged over all vehicles in the simulation
- Total number of received packets as a function of priority averaged over all vehicles in the simulation

DCC and MAC delays:

- Mean, maximum, and standard deviation of the delay in the DCC averaged over all vehicles in the simulation
- Mean, maximum, and standard deviation of the delay in the MAC averaged over all vehicles in the simulation

Duty cycle:

According to coexistence studies with Intelligent Transport Systems (ITS), there will be a need to limit the peak duty cycle within a measurement interval of 1 s. In order to get an idea on typical duty cycles in a DCC controlled C2C communication system, the duty cycle will be calculated for all vehicles within the simulation. Thereby, the duty cycle is defined by the accumulated PHY transmit time within a sliding window of 1 s and therefore includes packets transmissions of all four priorities.

The following plots will be generated:

- The duty cycle as a function of time will be plotted for 9 selected vehicle IDs (one on each lane and the crashed car with ID0). The same set of vehicles will be used for the three simulations using DCC variant A, B and C.
- The mean and maximum duty cycle within simulation time plotted for all vehicles. When calculating the maximum duty cycle, there are two different variants. The first one considers the duty cycles at all vehicle positions, while the second one considers only the values calculated at vehicle positions in the middle of the highway section and skips the ones near the border. The reason is that there are no vehicles outside the highway section and the channel load is typically significantly smaller at the border than in the middle. A vehicle driving near the border might then transmit its packets with a higher packet rate as it would be the case, if these neighbours would be present.

Position error:

The calculation of the position error will be based on CAMs only ([12]). Any positioning information in DENMs (e.g. in the GeoNetworking header) will be not considered, as this information is not forwarded to the facilities layer.

Three types of position errors will be calculated. The **first** one is the position error in case CAMs are generated according to the CAM generation rule without DCC limitations, transmitted without delay in DCC and MAC and received without collision by all vehicles in the simulation. This position error only depends on the vehicle position tracks and is not influenced by the DCC algorithm.

The **second** position error calculation considers the influence of the DCC algorithm as well as delays in the DCC, MAC, and PHY layer. Each time a CAM packet is transmitted by the PHY, the time since the last position update is calculated as shown in Figure 5-9.

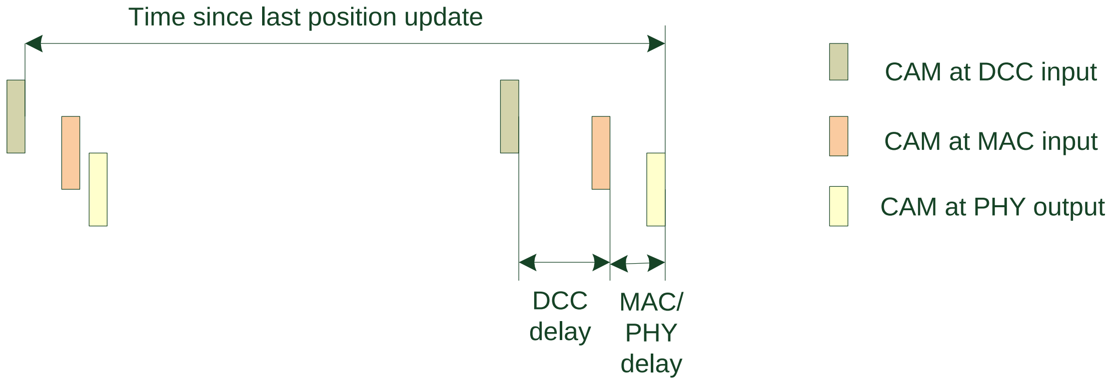


Figure 5-9: Calculations of positioning error

The time since the last position update is determined by the PHY transmit time of the actual CAM minus the arrival time of the last CAM in the DCC. Thereby it is assumed that there is no delay in between the CAM generation in the facilities layer and the arrival in the DCC, so that the position included in the last CAM corresponds to the vehicle position at the DCC arrival time[1]. Then the movement of the vehicle within this time interval is determined and stored as the actual position error.

The calculation of the **third** position error is identical to the second one except that it only considers CAM packet which have been successfully decoded at the receiver. Therefore, the third calculation additionally considers the impact of packet losses due to low SNR values caused by shadowing, large distances or packet collisions.

For all three position errors histograms will be presented. Additionally, mean, standard deviation, and maximum values will be compared for all three DCC variants based on the second position error.

Packet collision rate:

The packet collision rate is calculated based on the number of collided packets at each receiver input divided by the number of received packets with an SNR level, which allows for correct packet detection with a probability of more than 10% in a collision-free situation. The packet

[1] In case there are any additional delays, all three position errors will be affected the same way.

collision rate will be calculated for the phase prior to the crash with only CAM transmissions and for the phase after the crash with both, CAMs and DENMs on the air interface:

- Mean, median, and standard deviation of the packet collision rate in pre-crash phase (time ≤20s) averaged over all vehicles in the simulation
- Mean, median, and standard deviation of the packet collision rate in post-crash phase (time >20s) averaged over all vehicles in the simulation

5.2.2 Simulation results for the highway scenario with 128 vehicles

The simulation presented in section 5.1.3 considered DCC variant A. The same simulation has been repeated for DCC variant B, the modified DCC variant A, and DCC variant C.

As described in the previous section, the duty cycle will be shown for nine selected vehicles, one on each lane plus the crashed vehicle with ID0. The traces of these vehicles within 100s simulation time are presented in Figure 5-10.

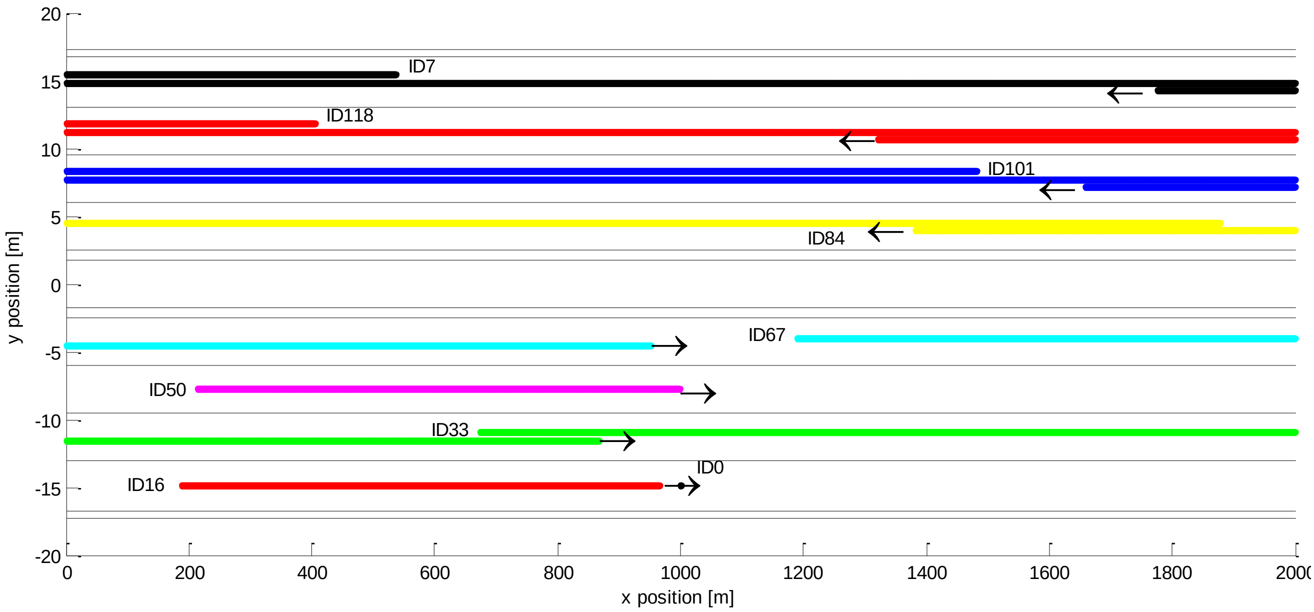


Figure 5-10: Traces of 9 selected vehicles, highway scenario with 128 vehicles

5.2.2.1 Results for DCC variant A

The resulting number of transmitted and received packets as well as the delays in the DCC and MAC are collected from Table 5-2, Table 5-3, and Table 5-4 and summarized in the table below.

DP1	DP1	CAM	DP3
CAM generation rule		592.4	
TxRequest	19.2	445.8	4323.6
TxPacket	19.2	445.8	117.5
RxPacket	1468	30299	5741
$\bar{d}_{DCC}[\mathrm{s}]$	0	0	0.12
$std(d_{DCC})\ [s]$	0	0	0.13
$\hat{d}_{DCC}[\mathrm{s}]$	0	0	1.00
$\bar{d}_{MAC}[\mathrm{ms}]$	0.31	0.62	0.93
$std(d_{MAC})\ [\mathrm{ms}]$	0.37	0.95	1.34
$\hat{d}_{MAC}[\mathrm{ms}]$	1.50	7.20	7.63

Table 5-5: DCC variant A, 128 vehicles

One additional row has been added showing the number of CAMs, which would have been generated according to the CAM generation rule if there were no limitations from the DCC. The mean number of CAMs generated by the facilities layer corresponds to 75% of that ideal number. Figure 5-11 shows that all vehicles generate less CAM packets than required according to the CAM generation rule.

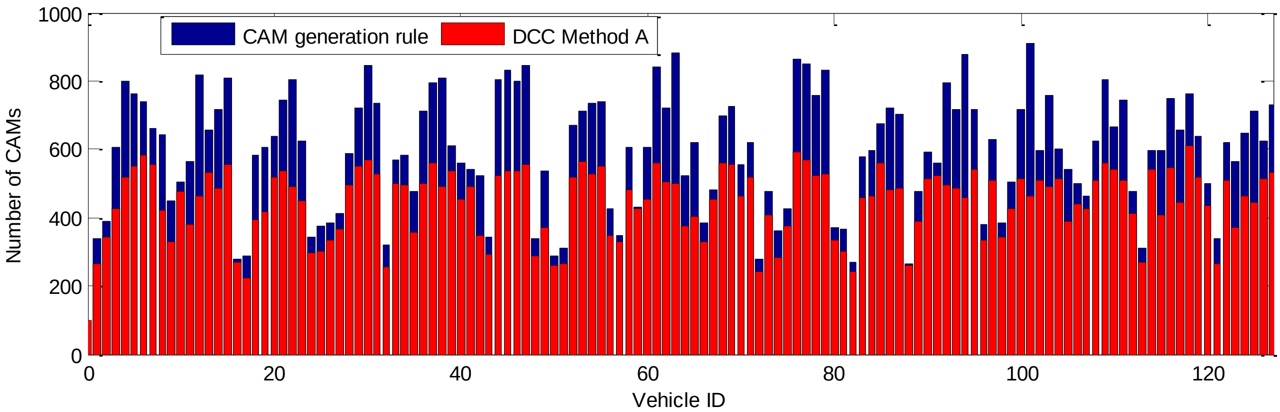


Figure 5-11: Number of CAMs according to CAM generation rule (blue) and at the input of the DCC (red), DCC variant A, 128 vehicles

As shown in Table 5-5, all DP1 and CAM packets are transmitted without delay in the DCC layer. The mean delay of DP3 packets is 120 ms with a standard deviation of 130 ms and a maximum value of 1.0 s. As expected the priority has impact on the delay in the MAC. The smallest MAC delay is measured for DP1 packets with a mean value of 0.31 ms, while the value is three times higher for DP3 packets. Nevertheless, the MAC delay is negligible since it is still under 1 ms on average with some outliers of up to 7 ms. A vehicle travelling in 110 km/h is moving 30 cm in 10 ms and 3 cm in 1 ms.

In a next step, the transmit duty is calculated for all vehicles. As the duty cycle directly depends on the actual DCC state, the state is shown in Figure 5-12 as a function of time for 9 selected vehicles. Low channel states can be observed in the first 20 s prior to the crash and in case a vehicle leaves the section and re-enters it. During this time the duty cycle often reaches its maximum as DP3 packets from the DCC queue are transmitted with a relatively short packet distance. The duty cycle is presented in Figure 5-13.

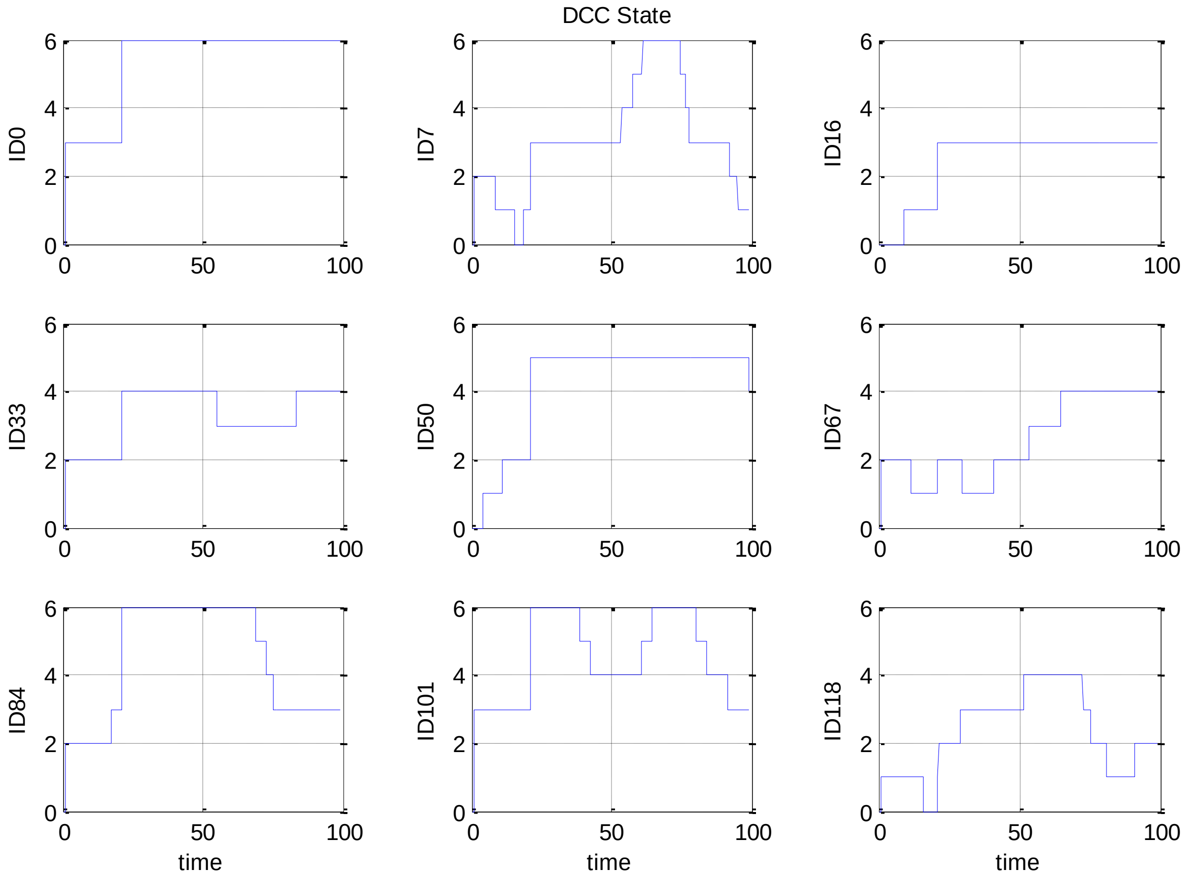


Figure 5-12: DCC state for 9 selected vehicles, DCC variant A, 128 vehicles

Note that the higher transmit duty cycle at the border is caused by the significantly smaller number of neighbours.

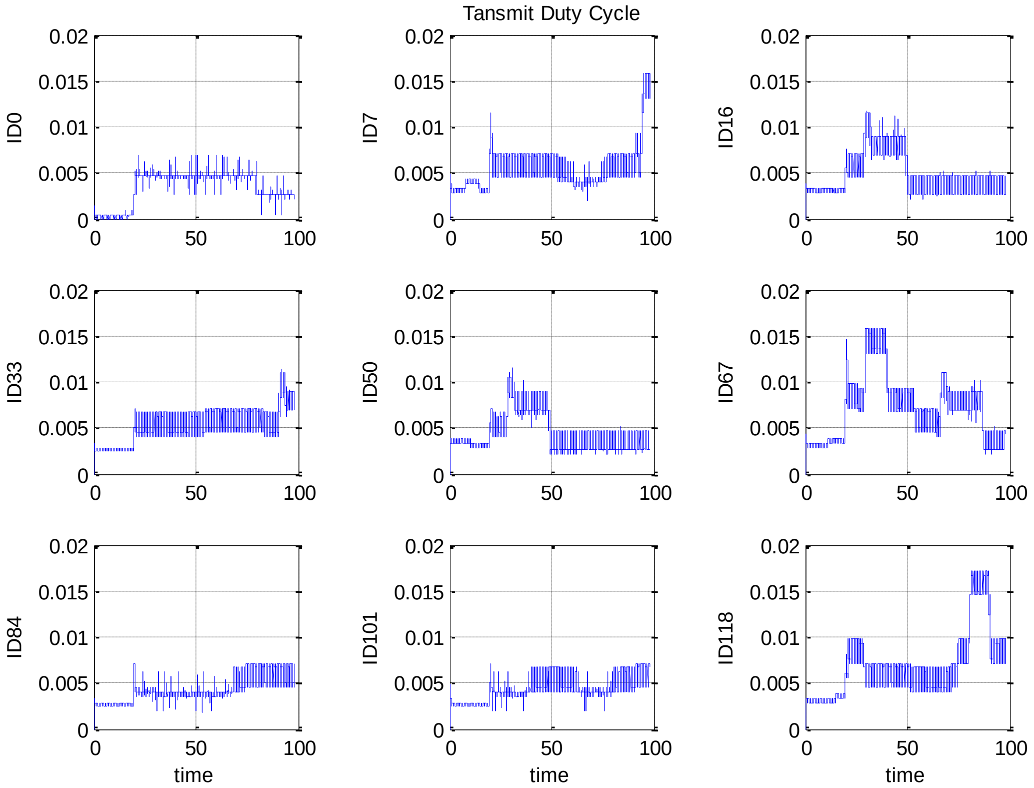


Figure 5-13: Duty cycle for 9 selected vehicles, DCC variant A, 128 vehicles

The mean and maximum duty cycle for all vehicles are shown in Figure 5-14 . The blue line indicates the mean value which is in the order of 0.5 % for all vehicles. The green line corresponds to the maximum duty cycle value, where all vehicle positions are considered. Finally, the values corresponding to vehicle positions near the border of the highway section are skipped, so that the red line corresponds to the maximum duty cycle in the middle of the highway section. Vehicles driving in the upstream direction are marked by an additional red diamond.

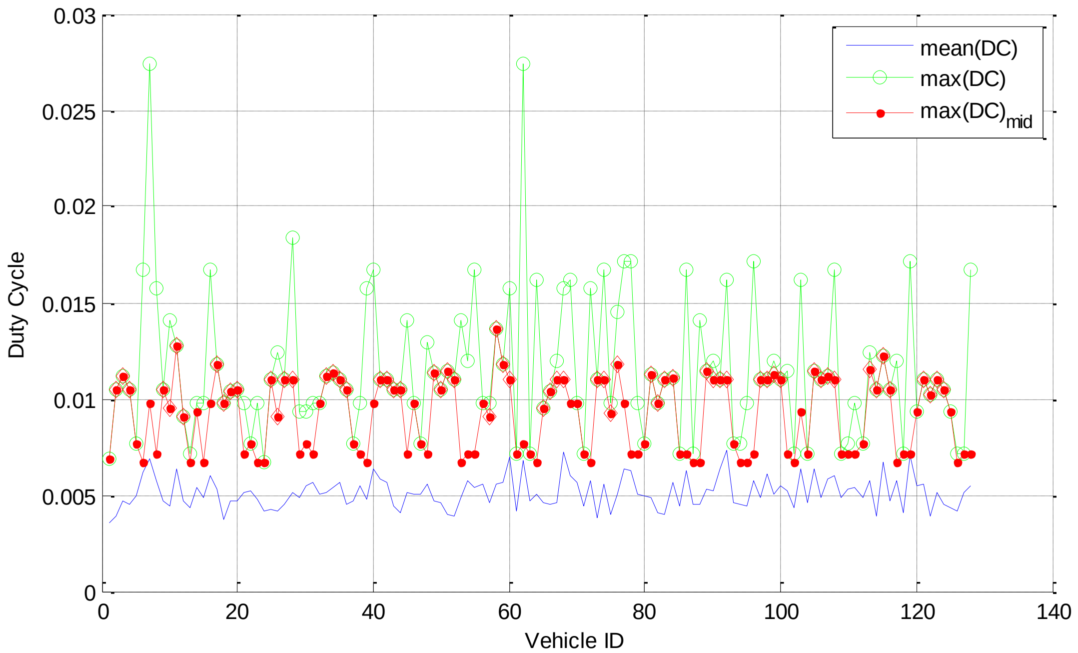


Figure 5-14: Mean and maximum duty cycle, DCC variant A, 128 vehicles

Looking at the results of the green line, duty cycles of more than 2.5 % can be observed. These high duty cycles belong to positions near the border of the highway section, as the duty cycle in the middle of the highway is significantly smaller and always below 1.5%. Vehicles driving in the upstream direction typically have a higher peak duty cycle than vehicles in the downstream direction, because they are sending DP1 packets in parallel to CAM and DP3 packets. As the duration of the “traffic jam ahead” DP1 packet is much longer than the duration of a CAM (see Table 3-1), the additional DP1 packet transmissions more than compensates for the reduced number of CAMs due to speed reduction.

5.2.2.2 Results for DCC variant B

Then the same simulation is repeated using DCC variant B. The DCC state adaptation and the measured and filtered channel load are shown in Figure 5-15 for vehicle ID2. Comparing the results to those in Figure 5-5, the measured channel load seems to be quite similar in the first 70 seconds. For the remaining 30 seconds the channel load is slightly higher for DCC variant B. The DCC channel state is different, but it has to be taken into account that the two variants are using different channel load thresholds. In DCC variant B *Active 2* corresponds to a channel load of 27% to 35%, while *Active 4* in DCC variant A corresponds to 30%-35%, which is quite comparable.

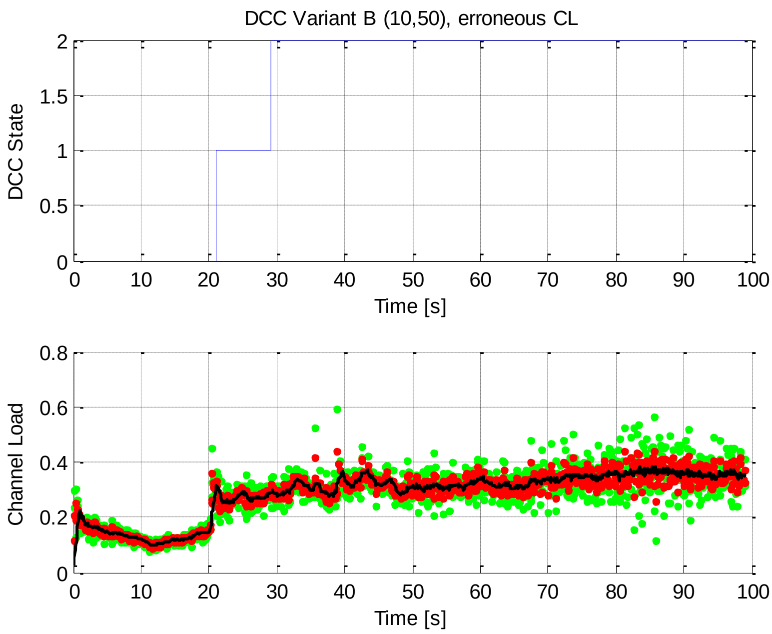


Figure 5-15: DCC state adaptation and measured channel load of vehicle ID2 for DCC variant B with NDL_TimeUp =1s, $NDL\_TimeDown$ =5s, 128 vehicles

While DCC delays in DCC variant A have been only measured for DP3 packets, it is more complicated for DCC variant B, as the transmit times for DP1, CAM, and DP3 packets are strongly correlated due to the common minimum packet distance requirement. An example for the resulting DCC delay and the number of packets in the DCC queue is shown in Figure 5-16 and Figure 5-17 for vehicle ID2.

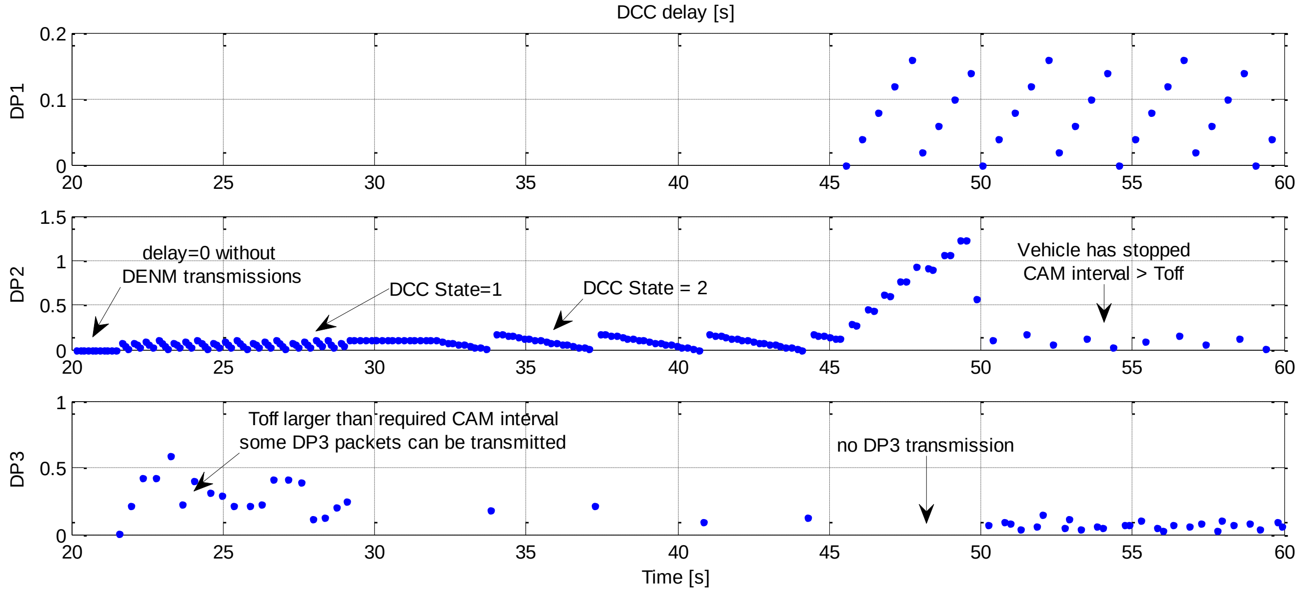


Figure 5-16: Priority dependent DCC delay for vehicle ID2 in the highway scenario with 128 vehicles

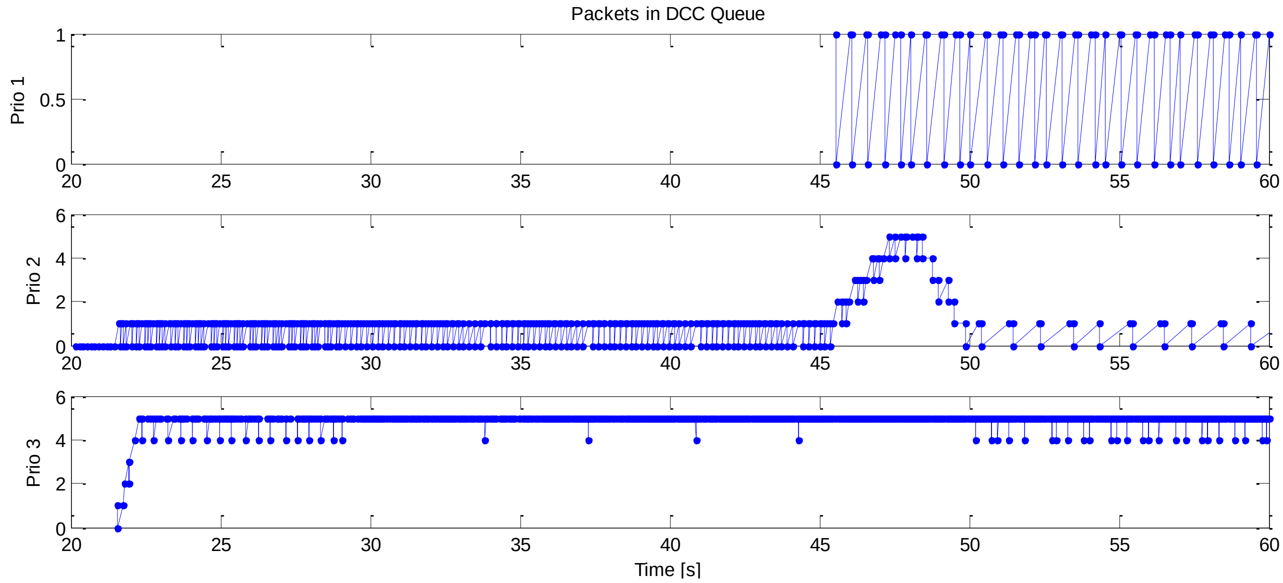


Figure 5-17: Priority dependent number of packets in the DCC buffer for vehicle ID2 in the highway scenario with 128 vehicles

There is no DCC delay for CAM packets prior to the first DP3 transmission at 21.5 s (see plot in the middle of Figure 5-16). The CAM generation rule requires a CAM update interval of 131 ms, while packet distances of 60 ms are allowed in *Relaxed* state. Hence, the CAM packets arriving in the DCC can be directly forwarded to the MAC and all DCC queues are empty as shown in Figure 5-17.

After the crash at 20 s the channel load significantly increases and the channel state changes to *Active 1* for 8 seconds and then to *Active 2* at time 29s as shown in Figure 5-15. *Active 1* corresponds to the minimum packet distance of 100 ms, which is still allows for a higher packet rate than required by CAM generation rule. When the first DP3 packets arrive at the DCC after 21.5 s, some DP3 packets can be transmitted in between the CAM packets. Looking at the number of DP3 packets in the corresponding DCC queue (lower plot in Figure 5-17), the arrival time is higher than the allowed transmit rate, so that the DCC queue is quickly filled and the first DP3 packets are lost after 22.3 s due to a buffer overflow. A mixture of CAMs and DP3 packet is transmitted with exactly the minimum distance of 100 ms. Dependent on the last transmit time of a DP3 packet, the next CAM needs to be delayed in between 0 and 100 ms as shown by the plot in the middle of Figure 5-16.

By the time the channel state changes from *Active 1* to *Active 2* the vehicle ID2 starts reducing its speed as shown in Figure 5-2. As this decreases the CAM generation rate according to the CAM generation rule even the higher minimum packet distance of 180 ms allows for four DP3 transmissions at the cost of higher DCC delays for CAM packets up to 180 ms.

At time 41.3 s the vehicle starts to brake hard, resulting in a higher CAM generation rate. Four seconds later, the speed drops below 30 km/h and the triggering conditions are fulfilled, so that vehicle starts with its first DP1 transmission. As the DP1 packet repetition interval is 500 ms and therefore larger than the minimum packet distance of 180 ms in the DCC, CAMs are transmitted in between the DP1 packets. Nevertheless the number of transmitted CAMs is smaller than the number of CAMs arriving at the DCC input, so that some CAMs need to be buffered. Hence, the delay of CAMs increases to 1.2 s in between 45 s and 50 s. After 50 s the vehicle has stopped and CAMs are generated with the maximum CAM generation interval of 1000 ms. At this point in time the sum of the DP1 and CAM packet rate is 3 packets in 1000 ms requiring an average transmit interval of 333 ms which is higher than the allowed packet distance of 180 ms. Consequently, additional CAMs from the buffer can be transmitted, until all CAMs are sent. Only after the CAM buffer is empty, the DCC is allowed to transmit the next DP3 packet.

Due to the common transmit control of DP1, DP2 and DP3 packets, the number of DP3 packet transmissions significantly depends on the number of DP1 and DP2 packets arriving at the DCC input. Figure 5-18 shows much larger variations of the vehicle specific number of DP3 packet transmitted within the 100 s of simulation time compared to DCC variant A in Figure 5-8.

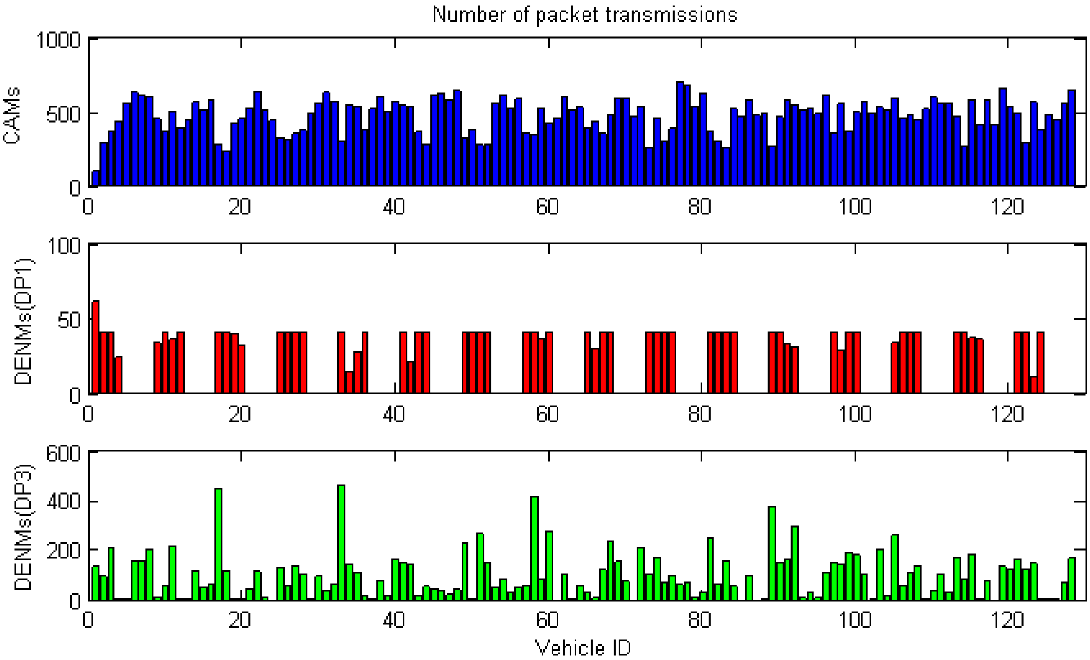


Figure 5-18: Number of transmitted packets as a function of priority. DCC variant B, 128 vehicles

The number of CAMs is only slightly higher for DCC variant B. It is still smaller than the number of CAMs which would have been required based on the CAM generation rule without DCC limitations as shown in Figure 5-19.

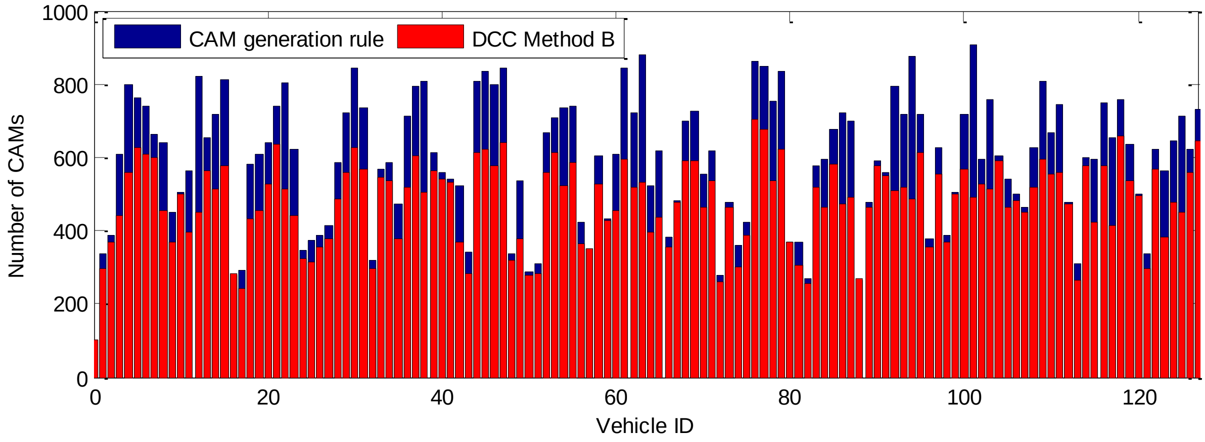


Figure 5-19: Number of CAMs according to CAM generation rule (blue) and at the input of the DCC (red), DCC variant B, 128 vehicles

The average number of DP1, CAM, and DP3 packets per vehicle transmitted within simulation time and the corresponding delay in DCC and MAC layer are summarized in Table 5-6.

DP1	DP1	CAM	DP3
CAM generation rule		592	
TxRequest	19.2	478	4043
TxPacket	19.2	476	103
RxPacket	1472	31644	5029
$\bar{d}_{DCC}$[s]	0.06	0.10	0.13
$std(d_{DCC})$ [s]	0.03	0.19	0.10
$\hat{d}_{DCC}$[s]	0.12	1.22	0.56
$\bar{d}_{MAC}$[ms]	0.29	0.54	0.83
$std(d_{MAC})$ [ms]	0.37	0.83	1.09
$\hat{d}_{MAC}$[ms]	1.60	6.38	5.24

Table 5-6: DCC variant B, 128 vehicles

A comparison with the results of DCC variant A in Table 5-5 proofs that both DCC variants transmit the same number of DP1 packets, while DCC variant B transmits slightly more CAMs and DP3 packets. Hence, the packet distances for DCC variant A seem to be somewhat more restrictive, although the difference is small. The main difference between the two variants is the DCC delay for DP1 packets with a mean value of 60 ms and a standard deviation of 30 ms and the DCC delay for CAM packets with a mean value of 100 ms and a standard deviation of 190 ms. These values have been zero in DCC variant A.

Due to the slightly higher number of packet transmissions in DCC variant B, the duty cycle is often higher in variant B than in variant A. Especially at the border of the highway section, when the DCC state reduces to *Relaxed*, DCC variant B allows for a higher transmit rate than variant A. A maximum duty cycle above 2.5 % can be observed for some vehicles.

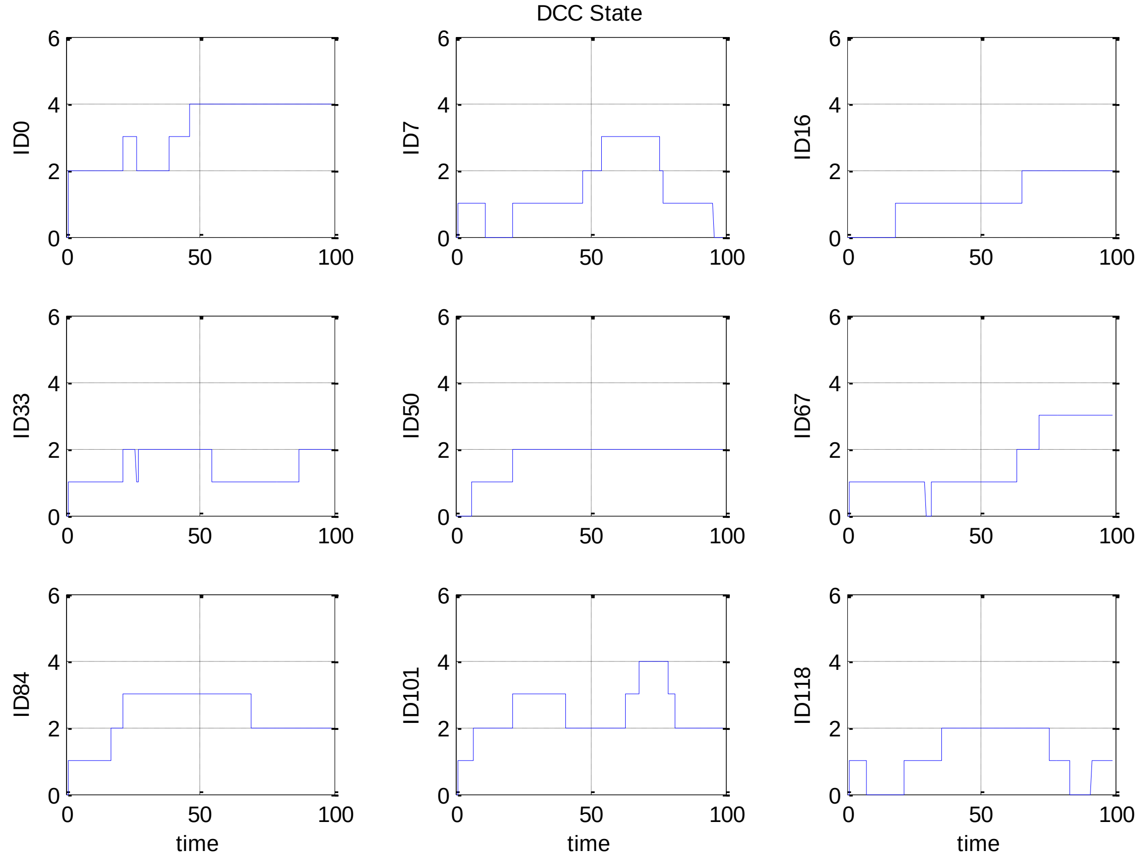


Figure 5-20: DCC state for 9 selected vehicles, DCC variant B, 128 vehicles

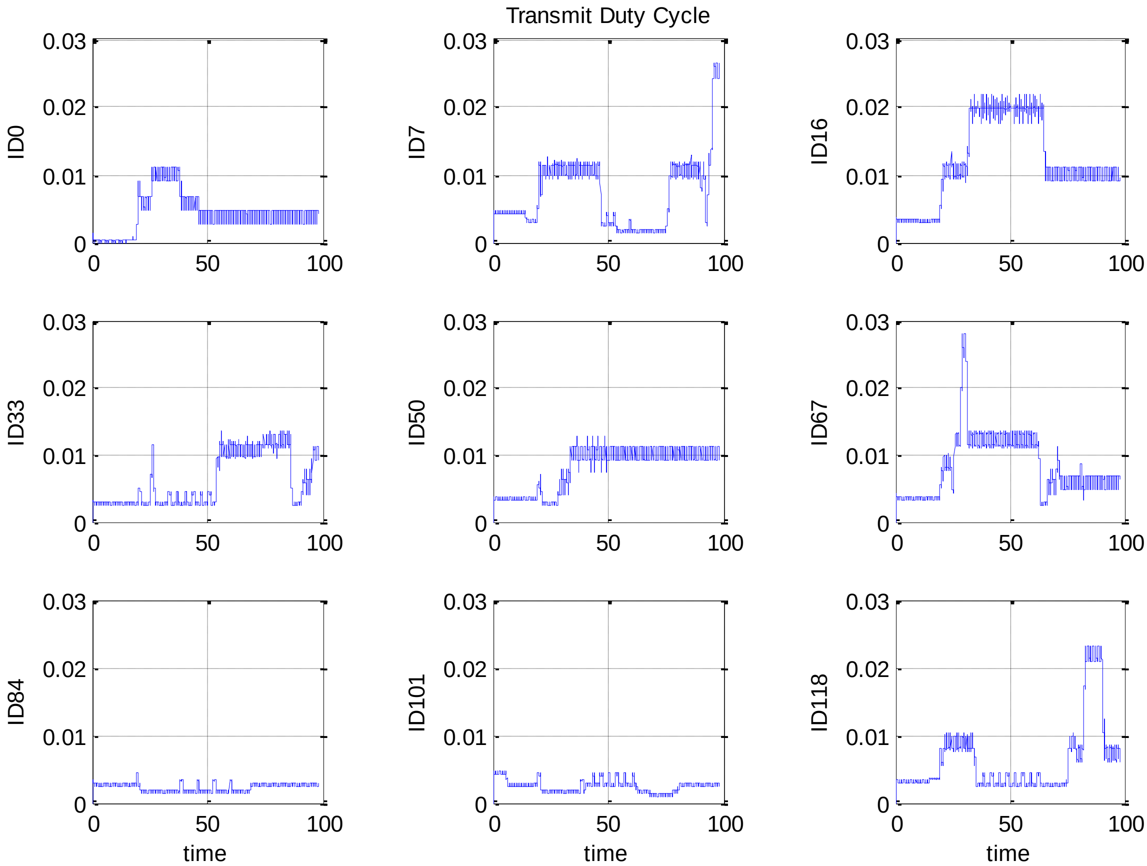


Figure 5-21: Duty cycle for 9 selected vehicles, DCC variant B, 128 vehicles

Figure 5-22 summarizes the mean and maximum duty cycles for all vehicles using DCC variant B. Compared to the same plot for DCC variant A in Figure 5-14, DCC variant B seems to result in higher differences for the mean and maximum duty cycle among the vehicles.

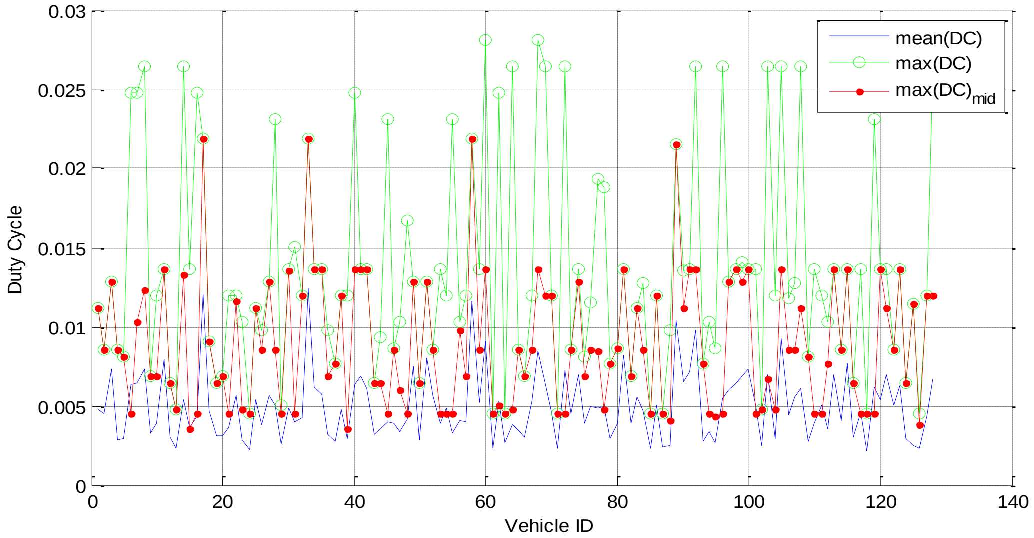


Figure 5-22: Mean and maximum duty cycle, DCC variant B, 128 vehicles

The reason might be that two vehicles at different speed will have different duty cycles even if they are in the same DCC state. The high speed vehicle will simply transmits more CAMs, while the low speed vehicles transmits a smaller number of CAMs und much longer DP3 packets whenever possible.

5.2.2.3 Results for modified DCC variant A (DCC variant C without DC limitation)

The modified DCC variant A uses the concept of DCC method A with modified CL threshold and packet distances as specified in Table 3-6. The DCC states in Figure 5-23 are therefore different from the states of DCC variant A, which are shown in Figure 5-5. Nevertheless, the measured channel load seems to be almost identical

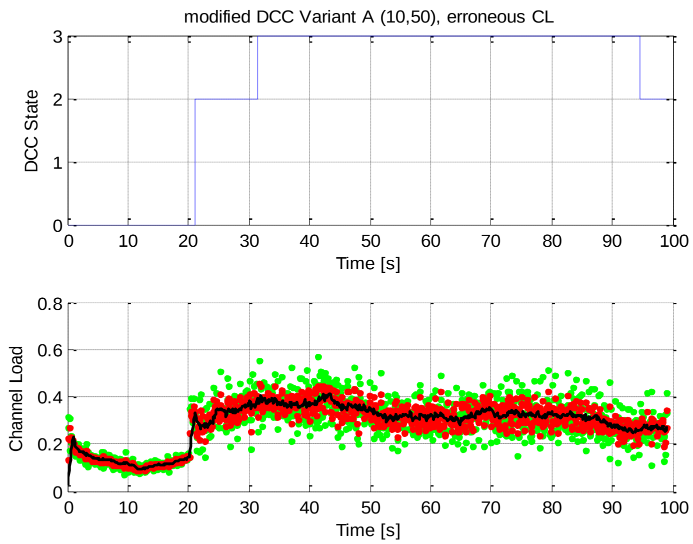


Figure 5-23: DCC state adaptation and measured channel load of vehicle ID2 for modified DCC variant A with NDL_TimeUp =1s, $NDL\_TimeDown$ =5s, 128 vehicles

The transmitted and received packets of all three priority levels are summarised in Table 5-7 together with delays in DCC and MAC layer.

DP1	DP1	CAM	DP3
CAM generation rule		592	
TxRequest	19.2	449.9	4436.6
TxPacket	19.2	449.9	115.2
RxPacket	1470	30754	6262
$\bar{d}_{DCC}$[s]	0	0	0.12
$std(d_{DCC})$ [s]	0	0	0.13
$\hat{d}_{DCC}$[s]	0	0	0.92
$\bar{d}_{MAC}$[ms]	0.32	0.65	1.14
$std(d_{MAC})$ [ms]	0.40	1.05	1.54
$\hat{d}_{MAC}$[ms]	1.70	8.10	8.65

Table 5-7: DCC variant A with the new channel thresholds, 128 vehicles

Comparing the results to the outcome of the original DCC variant A in Table 5-5 the values are quite similar. The number of transmitted and received CAMs is slightly higher and the reception rate for DP3 packets is better as more DP3 packets are received although a lower number of DP3 packets are transmitted. Nevertheless, the differences are small.

The number of transmitted packets within a simulation time of 100 s is shown in Figure 5-24.

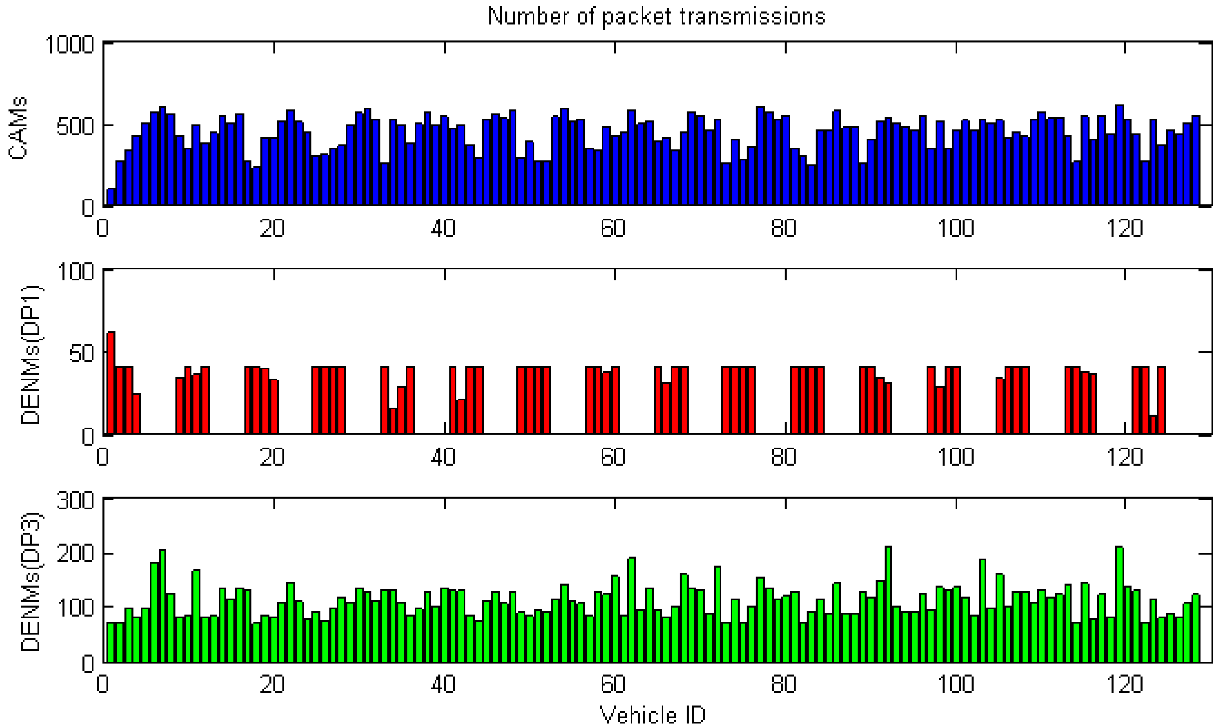


Figure 5-24: Number of transmitted packets as a function of priority, modified DCC variant A, 128 vehicles

Again, the results do not significantly differ from the results for the original DCC variant A shown in Figure 5-8, although the range of transmitted DP3 packets per vehicles is slightly larger with values in between 73 and 210 compared to 79-189 in the original version. The reason for the upper value could be a higher duty cycle at the border of the highway section as shown for example for the vehicle ID 118 in between 85 and 90 seconds (see Figure 5-26). During this time the DCC state becomes 0 (see Figure 5-25) corresponding to a DP3 packet distance of 100 ms, while the packet distance in the original variant A is equal to 186 ms.

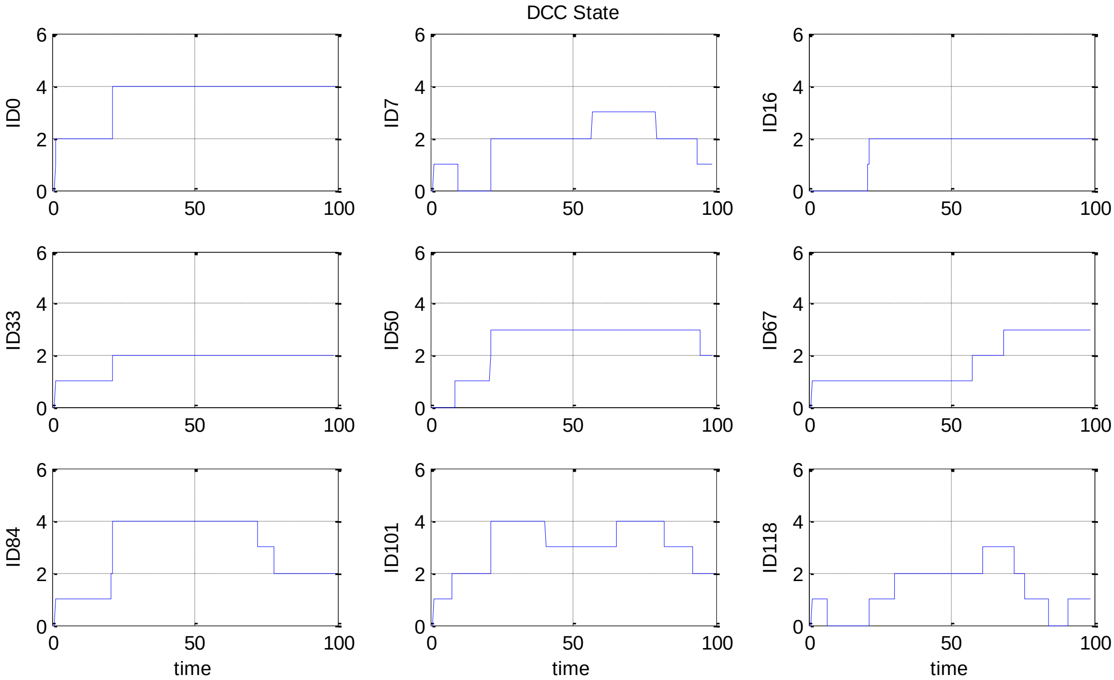


Figure 5-25: DCC state for 9 selected vehicles, modified DCC variant A, 128 vehicles

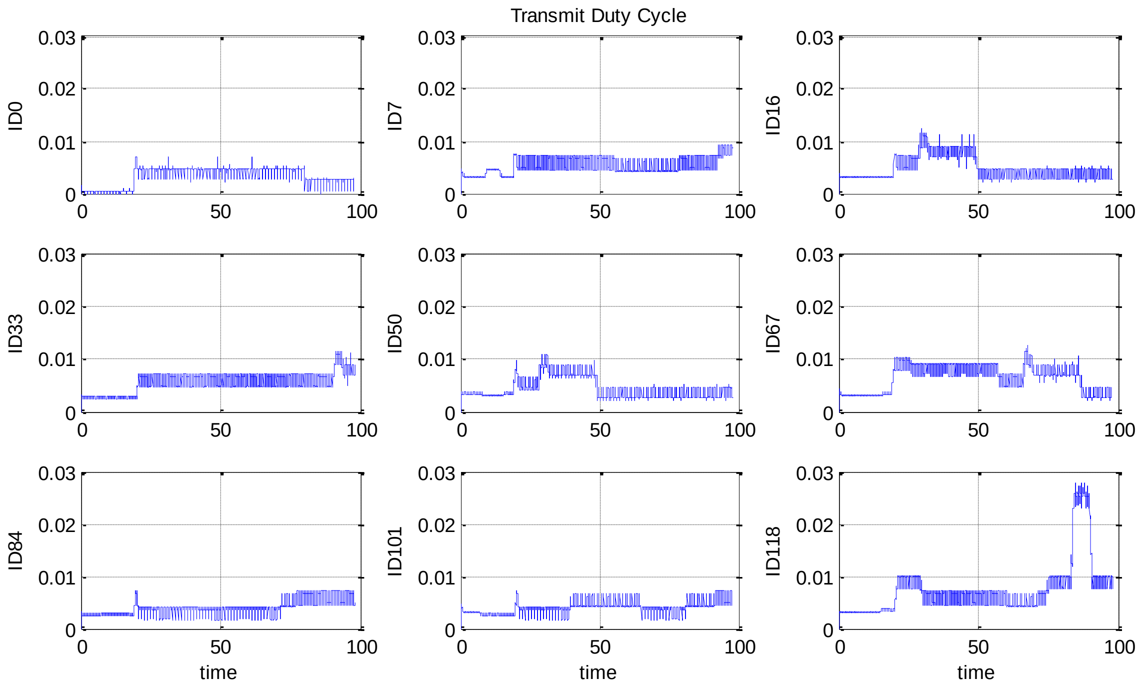


Figure 5-26: Duty cycle for 9 selected vehicles, modified DCC variant A, 128 vehicles

Nevertheless, most of the duty cycle values are quite comparable. This is confirmed by Figure 5-27, which shows the mean and maximum duty cycle using all values and only those in the middle of the highway section.

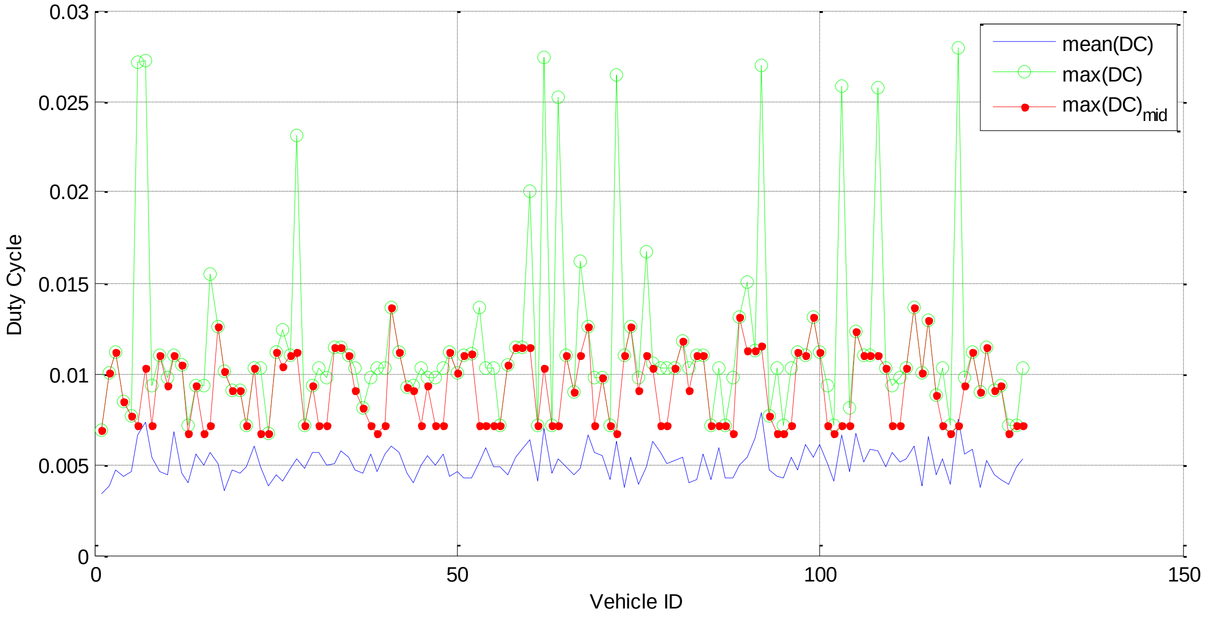


Figure 5-27: Mean and maximum duty cycle, modified DCC variant A, 128 vehicles

There are slightly more peak values above 2.5% at the border of the highway section than in the original DCC variant A (see Figure 5-14), although the number is still smaller than in DCC variant B (see Figure 5-22). The mean values as well as the maxima in the middle of the highway section are almost identical to the results of the original DCC variant A.

5.2.2.4 Results for DCC variant C

DCC variant C adds a duty cycle limitation for DP3 packet transmissions to the modified DCC variant A. DCC state and measured channel load in variant C and the modified variant A are exactly identical during the first 20 seconds when only CAMs are transmitted (see example for vehicle ID2 in Figure 5-23). After the crash the results are similar, although not identical as DP3 transmission times are different.

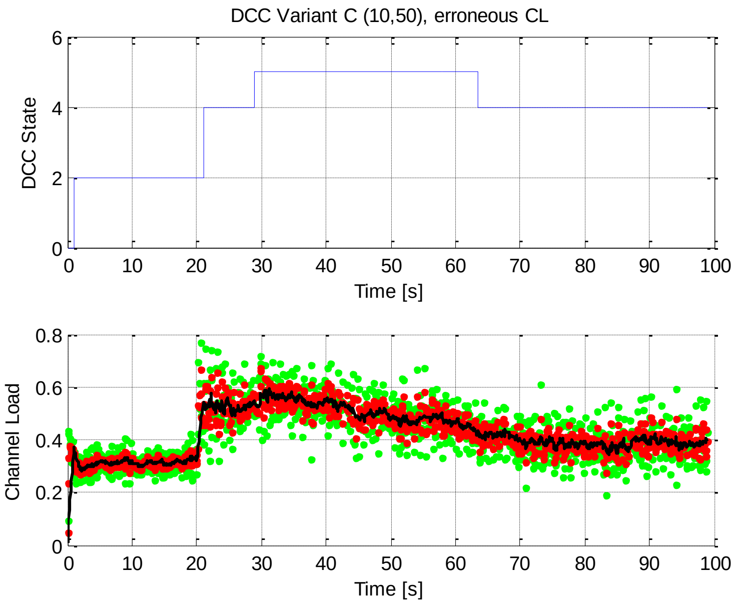


Figure 5-28: DCC state adaptation and measured channel load of vehicle ID2 for DCC variant C with NDL_TimeUp =1s, $NDL\_TimeDown$ =5s, 128 vehicles

The number of transmitted CAMs and DP1 DENMs are quite similar or even identical. The number of transmitted DP3 DENMs is slightly lower with values ranging in between 66 and 165 instead of 73 and 210 for the modified DCC variant A.

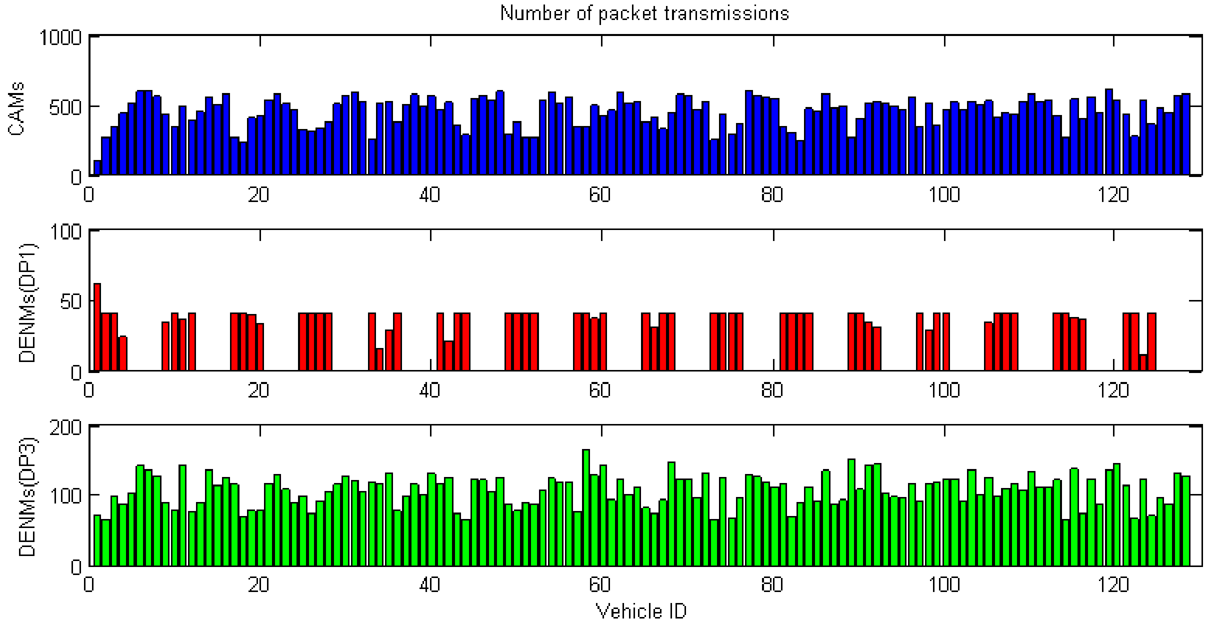


Figure 5-29: Number of transmitted packets as a function of priority. DCC variant C, 128 vehicles

The average number of transmitted and received packets per vehicle during the simulation time is shown in Table 5-8. The number of transmitted DP1 is identical when compared to the modified DCC version A (see Table 5-7), while the number of CAMs increases by 1.5% and the number of DP3 packets reduces by 6%. MAC delays for DP1 and CAMs are almost identical and even the increase in MAC and DCC delay for DP3 packets is very small.

DP1	DP1	CAM	DP3
CAM generation rule		592	
TxRequest	19.2	457.0	4359.3
TxPacket	19.2	457.0	108.2
RxPacket	1469	31232	6118
$\bar{d}_{DCC}[\mathrm{s}]$	0	0	0.12
$std(d_{DCC})\ [s]$	0	0	0.15
$\hat{d}_{DCC}[\mathrm{s}]$	0	0	1.08
$\bar{d}_{MAC}[\mathrm{ms}]$	0.30	0.64	1.26
$std(d_{MAC})\ [\mathrm{ms}]$	0.38	1.05	1.70
$\hat{d}_{MAC}[\mathrm{ms}]$	1.56	8.48	9.65

Table 5-8: DCC variant C, 128 vehicles

The impact of duty cycle limitations can be observed comparing the duty cycle of the vehicle with ID 118 in Figure 5-26 for the modified DCC variant A and in Figure 5-31 for DCC variant C. As described in the previous section this vehicle leaves and re-enters the simulated highway section in between 85 and 90 seconds. The DCC state is still zero during this time, but the duty cycle is now restricted to 1% in DCC variant C.

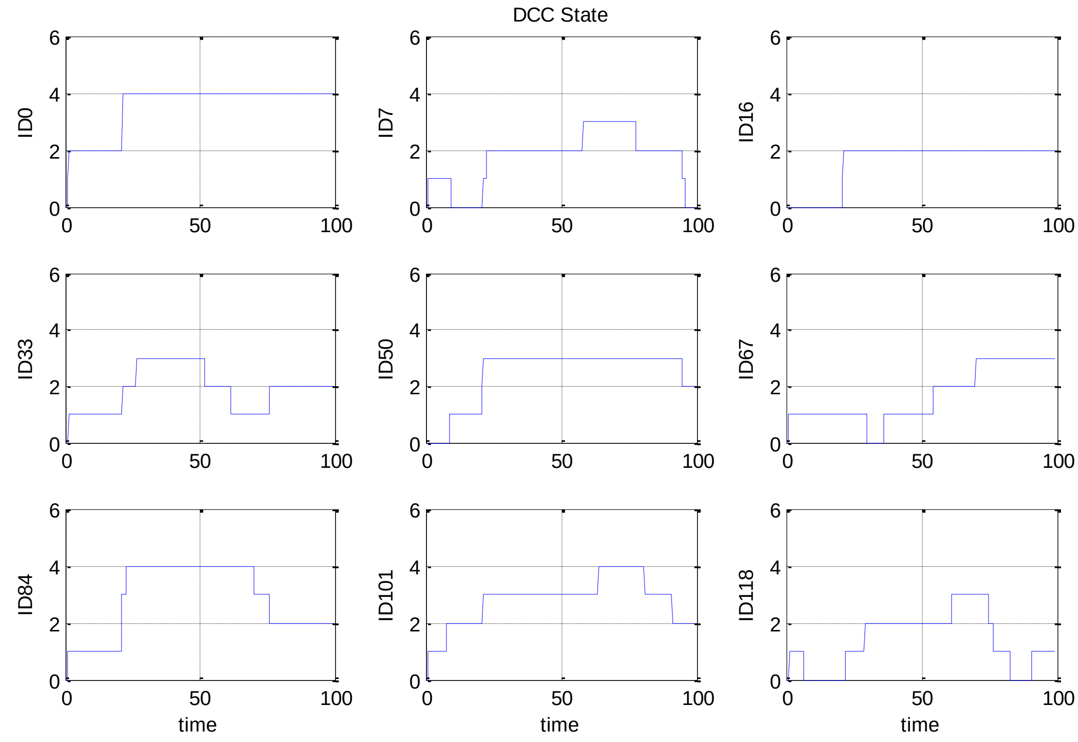


Figure 5-30: DCC state for 9 selected vehicles, DCC variant C, 128 vehicles

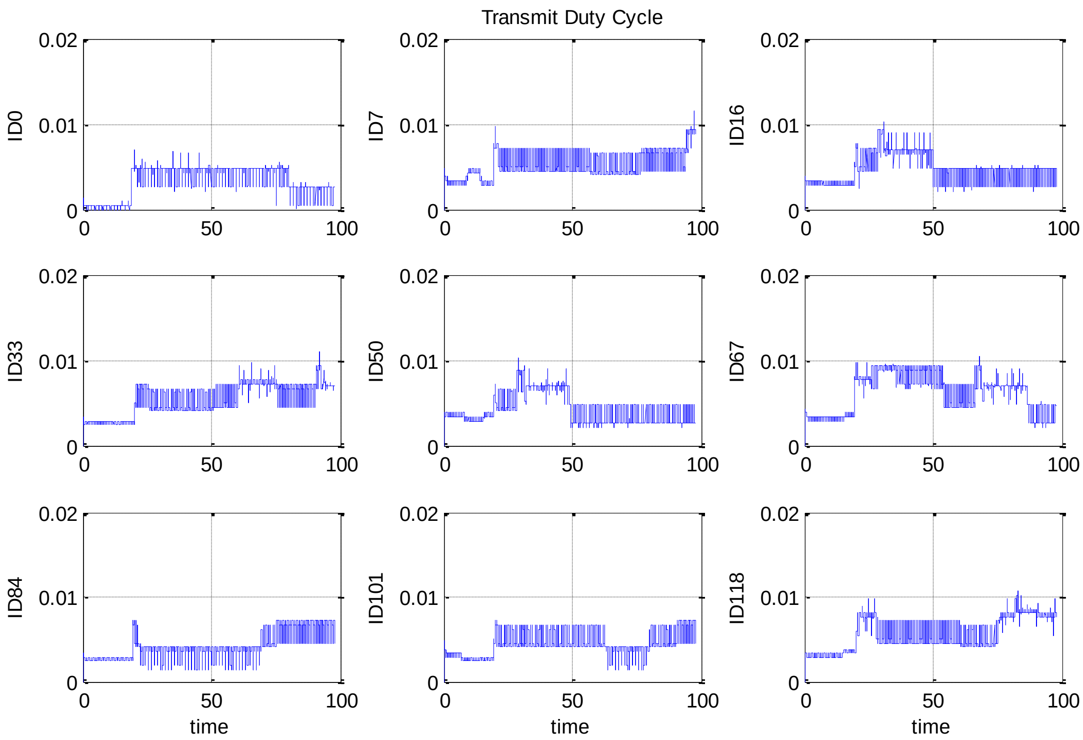


Figure 5-31: Duty cycle for 9 selected vehicles, DCC variant C, 128 vehicles

The limitation can be observed for all vehicles in the simulations, so that the peak duty cycles including the positions at the border of the highway sections are now much smaller than in the modified DCC variant A in Figure 5-27.

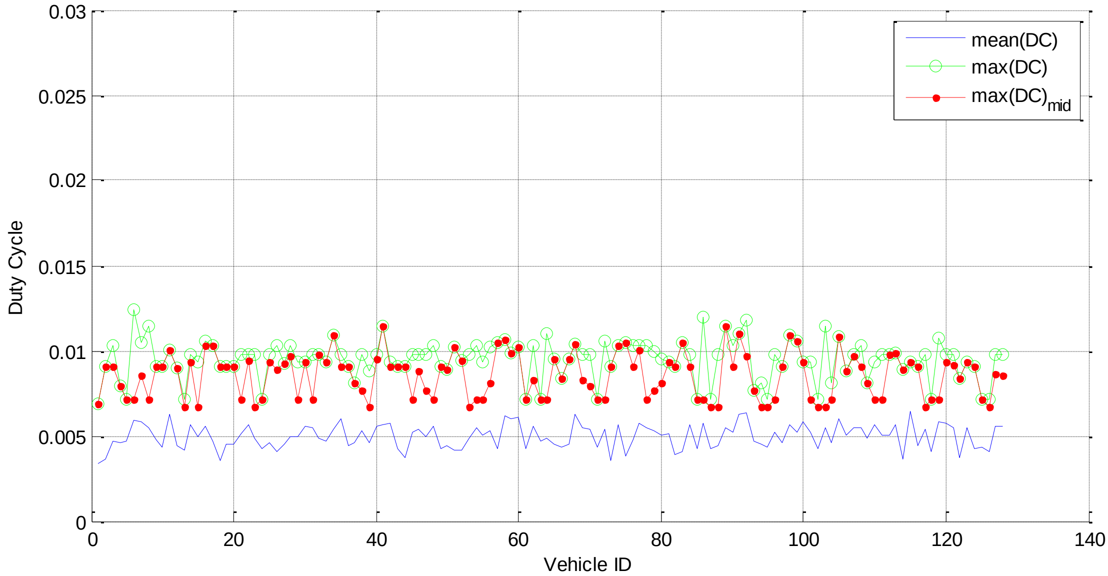


Figure 5-32: Mean and maximum duty cycle, DCC variant C, 128 vehicles

Nevertheless, the peak of the duty cycle can be slightly higher than the maximum duty cycle limit for DP3 transmissions. The reason is that the DCC can decide to transmit a DP3 packet due to a duty cycle below the limit. A DP1 or CAM packet arriving shortly after this time slightly increases the overall duty cycle, as this packet is directly forwarded to the MAC without duty cycle limitation. Nevertheless, the impact seems to be small.

5.2.2.5 Position error

As described in section 5.2.1 three different kind of position errors are calculated. The first one calculates the position error based on CAM generation rule without DCC limitations as described in section 3.1. In the simulations the condition is checked in 10 ms intervals, so that the typical position error using the CAM generation rule is slightly above 4 m as shown on the left side of Figure 5-33. In case the vehicle starts to brake hard approaching the traffic jam the accuracy is even higher. As soon as the vehicle has stopped the position error becomes zero independent of the CAM interval. For the forthcoming analysis all three position errors will be only calculated for moving vehicles.

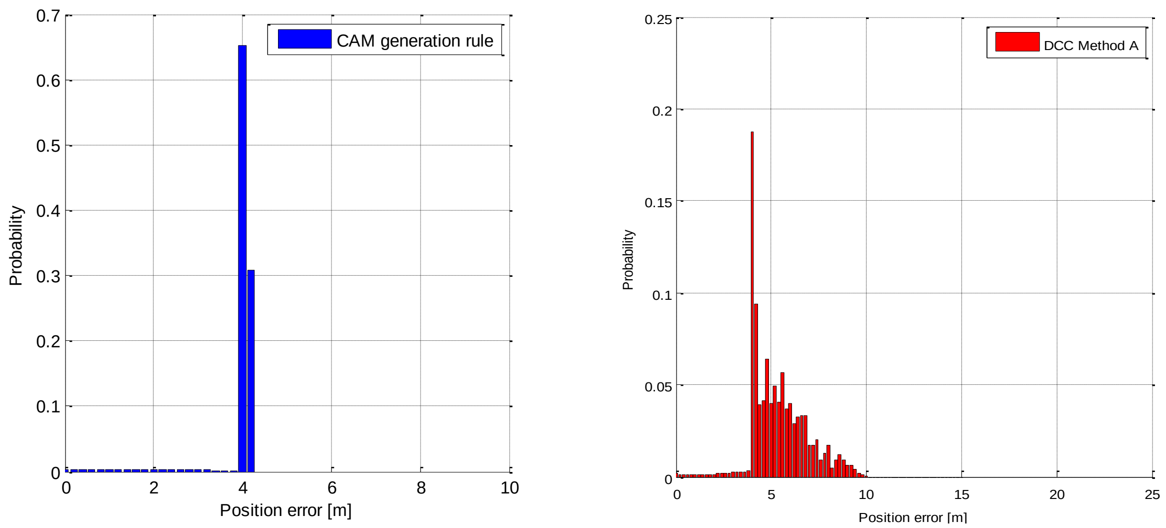


Figure 5-33: Probability of position error using CAM generation rule and no DCC limitations (left) and DCC variant A (right), 128 vehicles

The position error in the C2C system is affected by:

- Longer CAM intervals due to DCC restrictions (T_GenCam_Dcc)
- Delays in the DCC (only variant B)
- Delays in the MAC due to channel busy situations
- CAM packet reception failures due to collisions and small SNR

The resulting position error due to the first three effects is shown for DCC variant A on the right side of Figure 5-33. Packet losses are not considered in the calculation of the second position error. An error of around 4 m has the highest probability, but as soon as the DCC state increases after the crash the increased minimum packet distance results in position errors up to 10 m. Mean, maximum and standard deviation of the position error averaged over all vehicles are summarized in Table 5-9.

The results for variant B with a DCC buffer size of 5 packets for all priority classes are shown on the left side of Figure 5-34. A position error around 4 m is observed with a similar probability. Nevertheless, as soon as a vehicle generates "Traffic ahead" DENMs, the DP1 packet transmissions are preferred due to their higher priority. Hence, CAM need to be delayed or even skipped resulting in large position errors. Position errors of more than 20 m can be observed. Hence, mean, maximum, and standard deviation shown in Table 5-9 are significantly higher compared to DCC variant A.

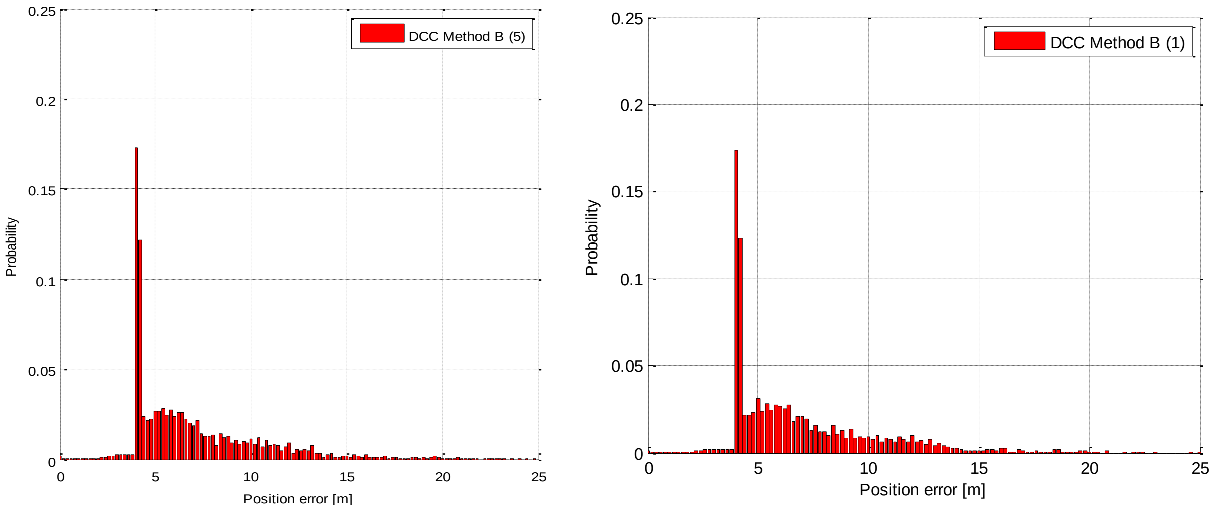


Figure 5-34: Probability of position error for DCC variant B with a CAM queue length of 5 (left) and 1 (right) based on CAM packet transmissions, 128 vehicles

Position Error	variant A	variant B (5)	variant B (1)	mod. variant A	variant C
mean	5.45	6.92	6.92	5.39	5.30
standard deviation	1.49	3.37	3.37	1.48	1.43
max	10.07	25.53	25.05	10.46	10.46

Table 5-9: Position errors for the different DCC variants in a highway scenario with 128 vehicles

Supposed that CAMs are the only packets with priority 2 as it is the case for all day1 scenarios, the DCC queue length could be reduced to only 1 packet. This guarantees that old CAMs are skipped and always the most recent CAM is transmitted. The resulting position error can be reduced by approximately 3 m during the DP1 transmission phase as shown in Figure 5-35.

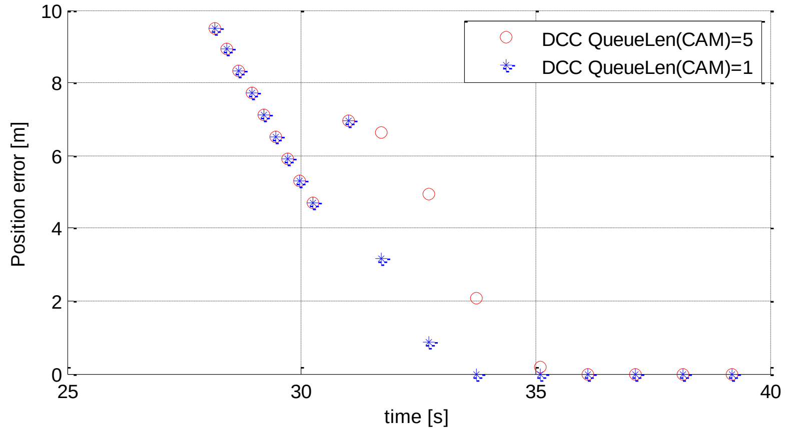


Figure 5-35: Resulting position error for a DCC queue length of 5 (red) and 1 packet (blue)

Nevertheless, the histograms shown in Figure 5-34 are almost identical for a CAM queue length of 5 and only 1 packet. This is confirmed comparing the mean, standard deviation and maximum position error summarized in Table 5-9 for the two DCC variant B implementations. The reason for the small effect is that only half of the vehicles are transmitting DP1 packets at all and outside the DP1 transmission phase there is never more than one CAM in the DCC queue, as the transmission of CAMs is preferred with regards to DP3 packets (see also the plot in the middle of Figure 5-17). Furthermore, the first “Traffic JAM ahead” message is triggered if the vehicle speed drops below 30 km/h and the other triggering conditions are fulfilled. Hence, the position only slowly changes during the DP1 transmission phase and a significant part of the DP1 packets are even transmitted after the vehicle stopped in the traffic jam. Hence, the improvements are very small. The effect is assumed to be larger in scenarios, where high priority packets are transmitted by vehicles at high speeds.

The performance degradation of DCC variant B with regards to variant A is caused by the delay of CAMs in the DCC in order to keep the minimum distance to an earlier DP1 or DP3 packet transmission. The performance can only be improved, if the layers above the DCC are able to adjust the packet transmissions such that the minimum distance in the DCC is correctly considered. This has been simple in DCC variant A, but is quite complicated in DCC variant B.

Hence, a new DCC variant C is proposed using a modified version of DCC variant A with an additional duty cycle limitation for DP3 packets. The position errors for DCC variant A with the new CL thresholds are shown on the left of Figure 5-36, while the results for DCC variant C are plotted on the right side.

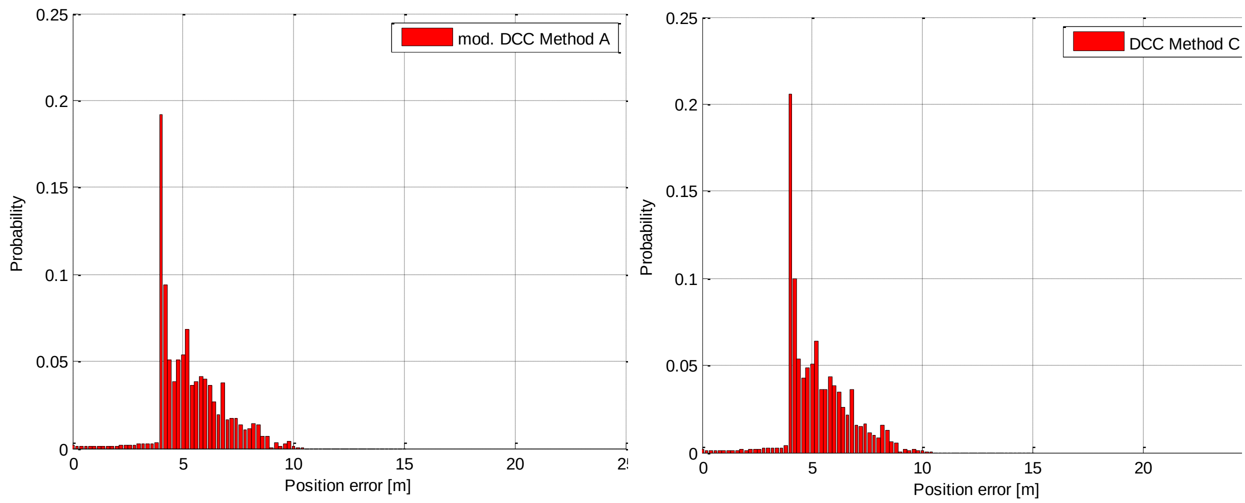


Figure 5-36: Probability of position error for modified DCC variant A (left) and DCC variant C (right) based on CAM packet transmissions, 128 vehicles

The results of these two approaches are almost identical, as it can also be observed from the statistical values listed in Table 5-9. Additionally, the results are almost identical to the results of the original variant A.

Finally, the position error based on successfully received CAMs is calculated taking CAM packet losses into account. The results are shown for DCC variant A on the left and DCC variant B on the right side of Figure 5-37. The performance of DCC variant B remains worse than DCC variant A.

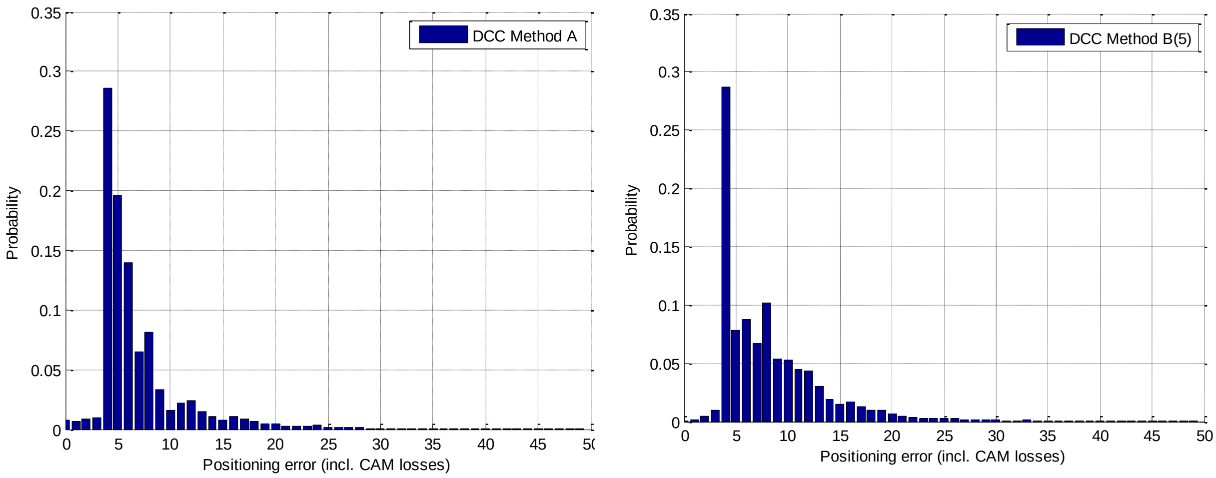


Figure 5-37: Probability of position error for DCC variant A (left) and DCC variant B (right) with a CAM queue length of 5 packets based on CAM packet receptions, 128 vehicles

The same analysis is done for DCC variant B with only 1 CAM in the DCC queue. The result shown on the left side of Figure 5-38 is almost identical to that of DCC variant B with up to 5 CAMs.

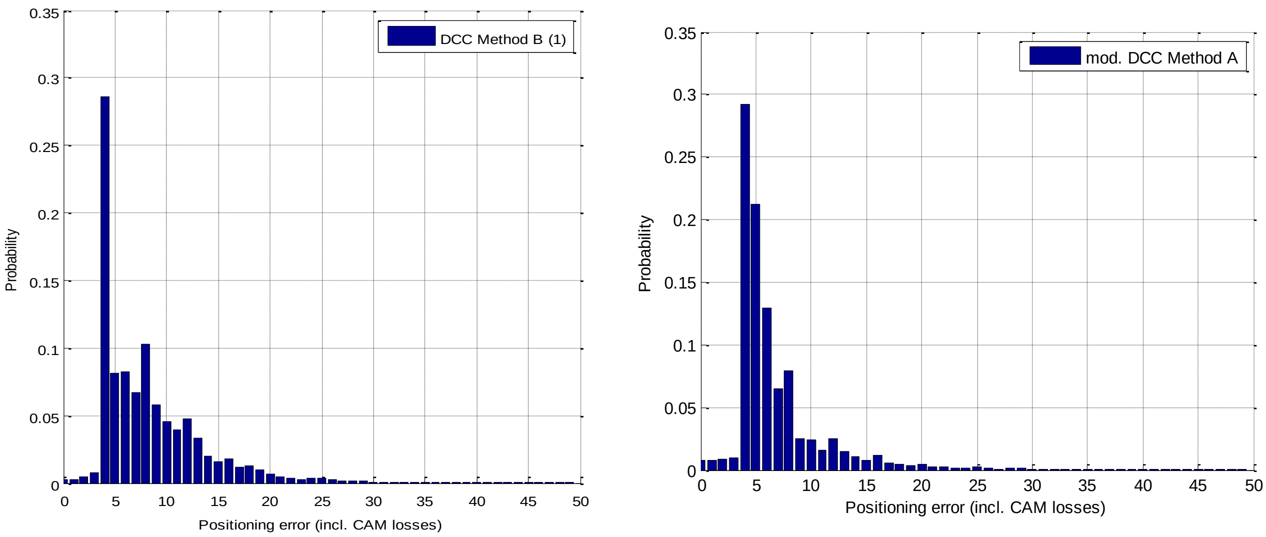


Figure 5-38: Probability of position error for DCC variant B with a CAM queue length of 1 (left) and the modified DCC variant A (right) based on received CAM packets, 128 vehicles

Next, the position error is calculated for the modified DCC variant A (higher channel load thresholds than variant A). The results on the right side of Figure 5-38 proof to be quite similar to those of the original DCC version A. Finally the results for DCC variant C are shown on the left side of Figure 5-39. There is almost no difference between DCC variant C and the modified variant A. The plot on the right side compares the cumulative distribution functions of DCC variant A, B, and C. In 90% an error below 10 m is observed in DCC variants A and C, while the error will be up to 14 m in DCC variant B.

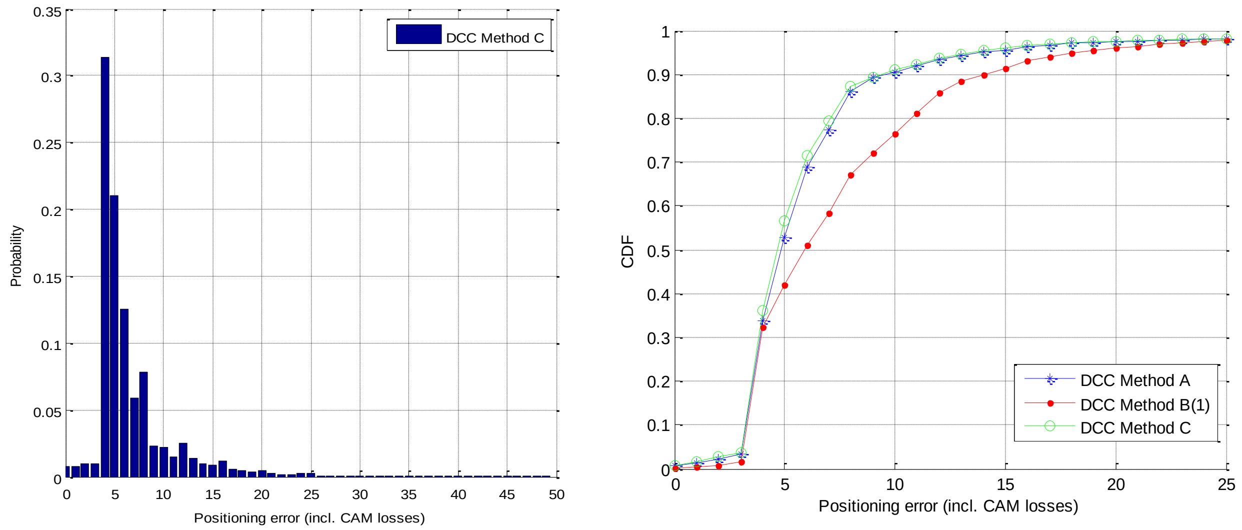


Figure 5-39: Probability of position error for DCC variant C (left) and cumulative distribution function of selected DCC variants based on received CAM packets, 128 vehicles

5.2.2.6 *Packet collision rates*

Packet collision rates are calculated for all DCC variants for the pre-crash phase and the post-crash phase. Results for the pre-crash phase are summarised in Table 5-10. The same values are obtained for the two implementations of DCC variant B with 1 and 5 packet positions in the CAM queue. The reason is that the facilities layer can provide CAMs with exactly the right minimum distances in case there are no DENM transmissions, so that CAMs are not delayed in the DCC. Additionally, the same results are obtained for the modified version of the DCC variant A and DCC variant C, as duty cycle limitations for DP3 packets have no impact in the pre-crash phase. The results for DCC variant A and its modified version are almost identical, while higher collision rates are obtained for DCC variant B due to the higher number of CAM transmissions.

Packet Collision Rate	variant A	variant B (5) / (1)	mod. variant A / variant C
mean	0.117	0.153	0.117
median	0.119	0.157	0.119
standard deviation	0.031	0.042	0.032

Table 5-10: Packet collision rates in the pre-crash phase, 128 vehicles

Although the results for the DCC variants are all different in the post-crash phase, there are only small differences. Additional DENM transmissions result in a packet collision rate of 20%.

Packet Collision Rate	variant A	variant B (5)	variant B (1)	mod. variant A	variant C
mean	0.211	0.204	0.2	0.205	0.201
median	0.202	0.202	0.196	0.198	0.194
standard deviation	0.057	0.051	0.054	0.054	0.053

Table 5-11: Packet collision rates in the post-crash phase, 128 vehicles

During the post-crash phase the traffic situation is different for each vehicle in the simulation. It depends on the actual vehicle position and the transmit activity of the neighbouring vehicles. The tables above show average values over all vehicles. Another approach is to investigate the collision rate as a function of the actual measured channel load. The simulator provides the number of collided and received packets as well as the filtered channel load value with an update rate of 10 Hz for each vehicle in the simulation. The data are collected from all vehicles and sorted according to the filtered channel load. The result is shown in Figure 5-40 for all three different DCC variants. The curves are almost identical, so that the collision rate is simply proportional to the channel load and no function of the DCC access scheme at least for low vehicles densities.

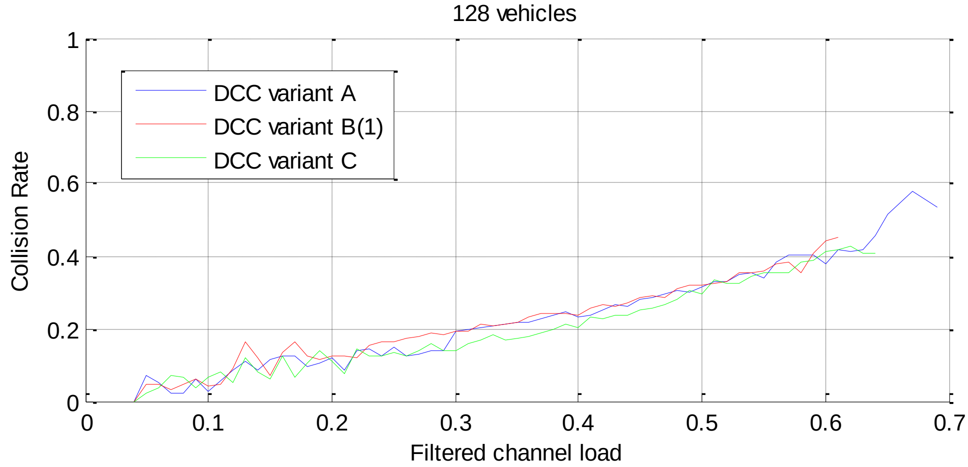


Figure 5-40: Collision rate as a function of filtered channel load for 128 vehicles, post-crash

The channel loads are quite similar for the three different DCC variants. DCC variant B tends to a slightly higher channel load during the pre-crash phase as shown on the left side of Figure 5-41. The probability functions for DCC variant A and C are almost identical.

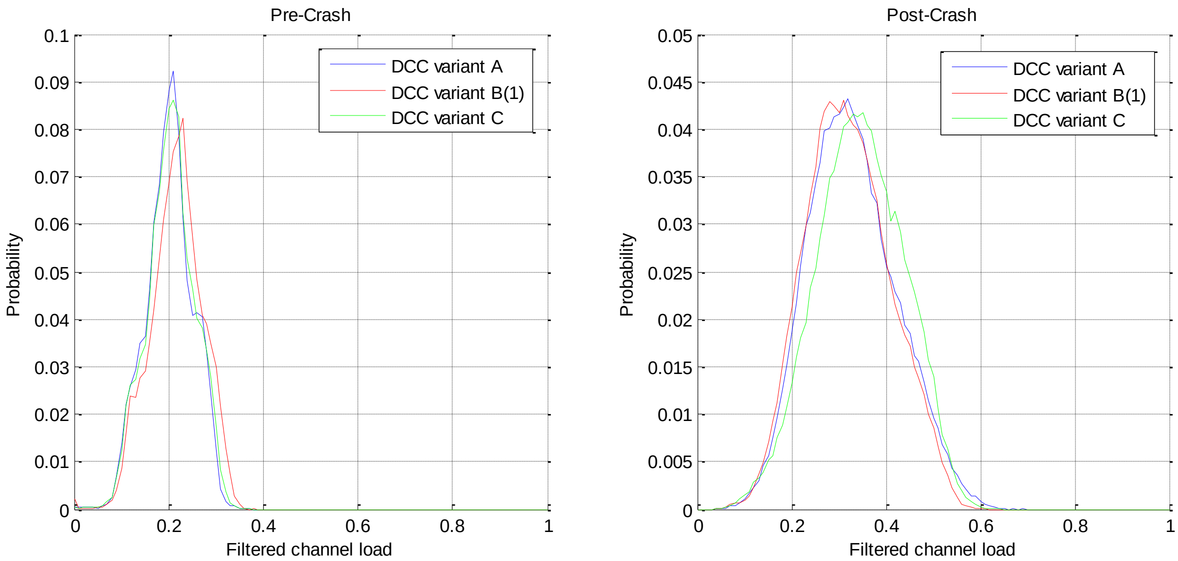


Figure 5-41: Probability function of the filtered channel load during pre-crash and post-crash phase, 128 vehicles

During the post-crash phase, the distribution of filtered channel loads is equal for DCC variant A and B, while DCC variant C has a slightly higher mean value. Nevertheless, the probability for high channel loads is even smaller than for DCC variant A. Mean value and standard deviation of the filtered channel load are listed for the pre-crash and post-crash phase in Table 5-12

	Filtered channel load	variant A	variant B (1)	variant C
Pre-crash	mean	20.7 %	22.1 %	20.9%
	standard deviation	5.0 %	5.4%	5.1%
Post-crash	mean	33.4 %	32.4%	35.0%
	standard deviation	9.4 %	8.9%	9.2%

Table 5-12: Packet collision rates in the post-crash phase, 128 vehicles

5.2.3 Simulation results for the highway scenario with 256 vehicles

In a next step, the number of vehicles in the simulation is doubled representing a medium traffic situation. Again, one vehicles is selected on each lane in order to look into the duty cycle as a function of time. The traces of the selected vehicles are shown in Figure 5-42.

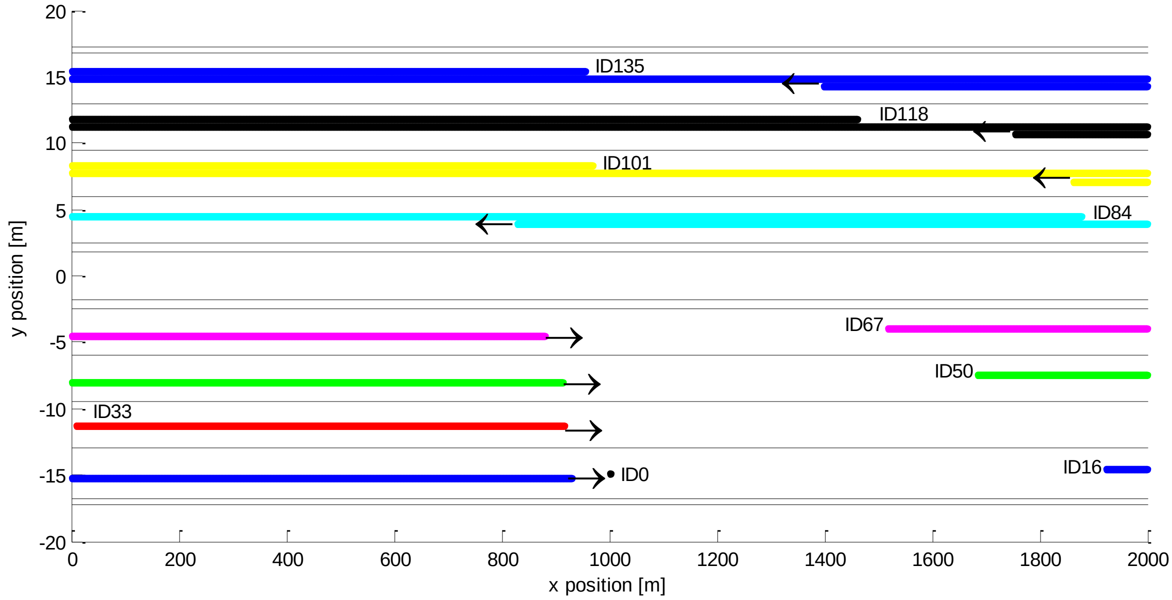


Figure 5-42: Traces of 9 selected vehicles, highway scenario with 256 vehicles

5.2.3.1 Results for DCC variant A

Due to the higher number of vehicles, the DCC state during the first 20 s with only CAM transmissions is already higher than in the simulation with 128 vehicles. An example in Figure 5-43 shows the DCC state and the measured and filtered channel load for vehicle ID2. A channel load of around 30% is measured prior to the crash resulting in a DCC state of either 3 or 4. After the crash the filtered channel load increases to 60% and then oscillates in between 40% to 60%. The corresponding DCC state is *Restricted*, which is maintained until the end of the simulation.

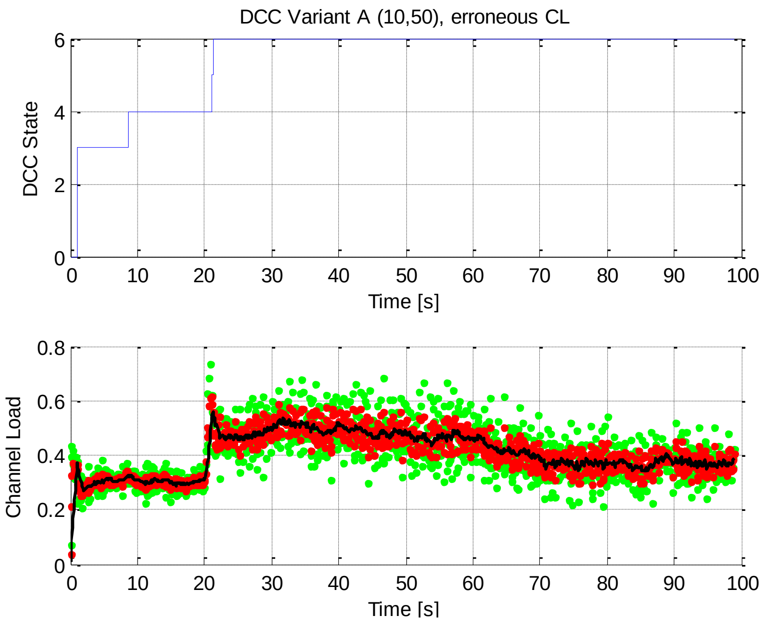


Figure 5-43: DCC state adaptation and measured channel load of vehicle ID2 for DCC variant A with NDL_TimeUp =1s, $NDL\_TimeDown$ =5s, 256 vehicles

The number of transmitted DP1, CAM and DP3 packets within the simulation time is shown for all vehicles in Figure 5-44. The number of CAMs is generally higher for those cars driving in the downstream direction than for the ones ending up in the traffic jam in the upstream direction.

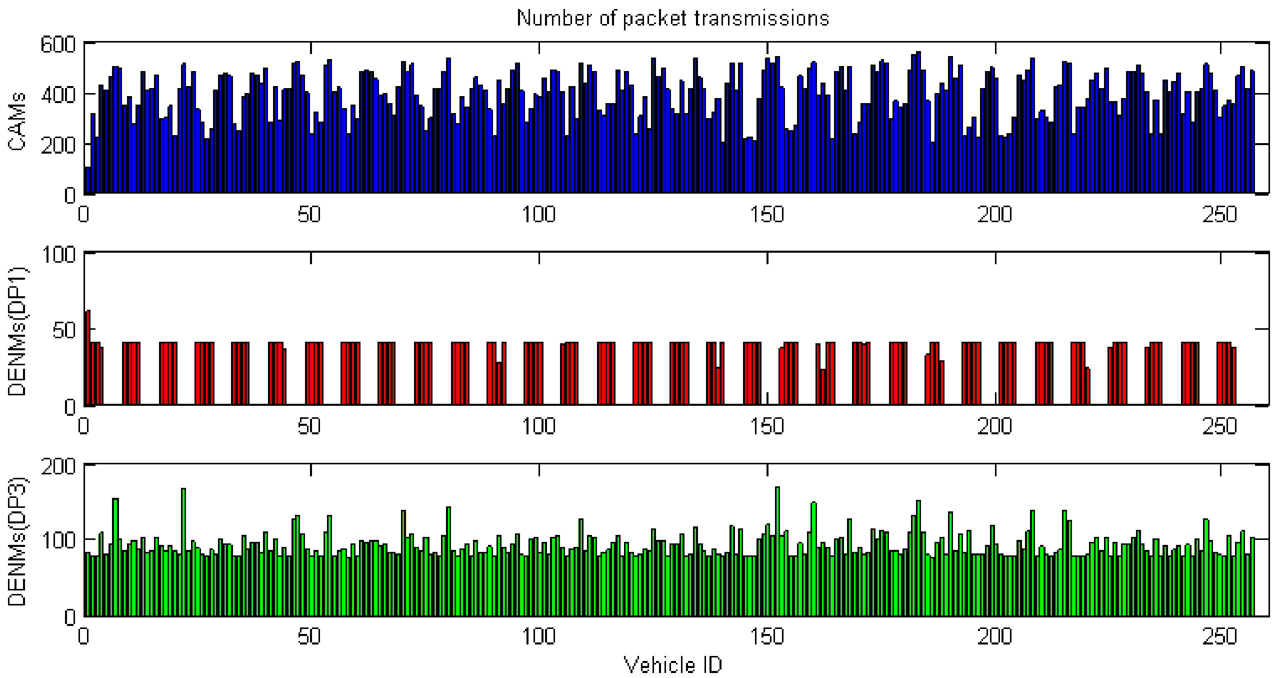


Figure 5-44: Number of transmitted packets as a function of priority, DCC variant A, 256 vehicles

DP1 packets are only transmitted by the crashed car (ID0) and those cars driving in the upstream direction while all vehicles transmit a quite similar number of DP3 packets. Due the higher DCC states the number of generated CAMs in the facilities layer is only 67% of the number of CAMs, which would result from the CAM generation rule without DCC limitation (see Figure 5-45). In the simulation with only 128 vehicles a ratio of 75% has been achieved.

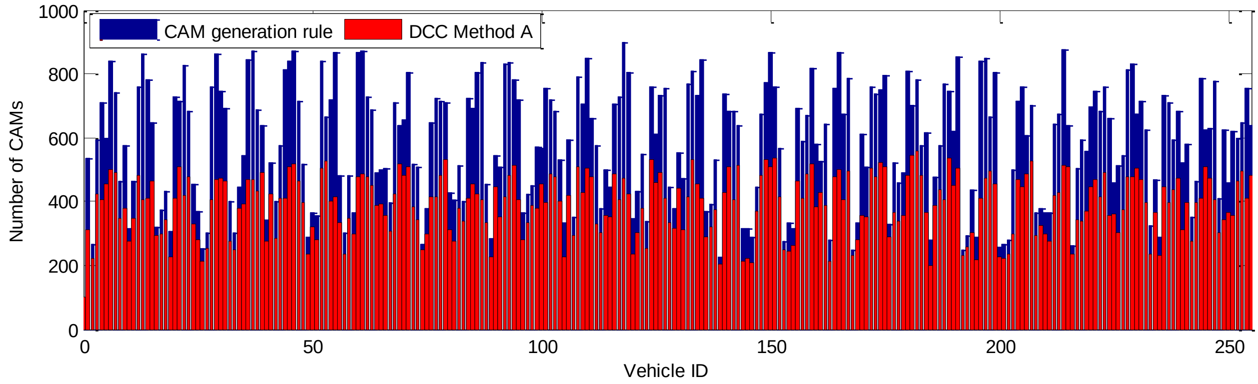


Figure 5-45: Number of CAMs according to CAM generation rule (blue) and at the input of the DCC (red), DCC variant A, 256 vehicles

The number of transmitted and received DP1, CAM, and DP3 packets within the simulation time as well as the delays in the DCC and MAC layer are summarized in Table 5-13.

DP1	DP1	CAM	DP3
CAM generation rule		583	
TxRequest	20.2	391	4627
TxPacket	20.2	391	94.5
RxPacket	1917	37058	4848
$\bar{d}_{DCC}$[s]	0	0	0.13
$std(d_{DCC})$ $[s]$	0	0	0.14
$\hat{d}_{DCC}$[s]	0	0	0.93
$\bar{d}_{MAC}$[ms]	0.48	0.80	1.41
$std(d_{MAC})$ [ms]	0.48	1.26	1.88
$\hat{d}_{MAC}$[ms]	2.01	9.64	10.57

Table 5-13: DCC variant A, 256 vehicles

Again, DP3 packets are the only ones delayed in the DCC layer with a mean delay of 130 ms and a standard deviation of 140 ms. All packets are delayed in the MAC due to the CSMA procedure, while the mean delay varies from 0.48 ms for DP1 packets to 1.41 ms for DP3 packets. The maximum delay can be significantly larger with 2 ms for DP1 and 10.6 ms for DP3 packets.

The DCC state and the duty cycle are shown for the 9 selected vehicles in Figure 5-46 and Figure 5-47, respectively. Most of the vehicles end up in DCC state 5 or 6 after the crash, while smaller DCC states typically corresponds to vehicles positions near the border of the highway section.

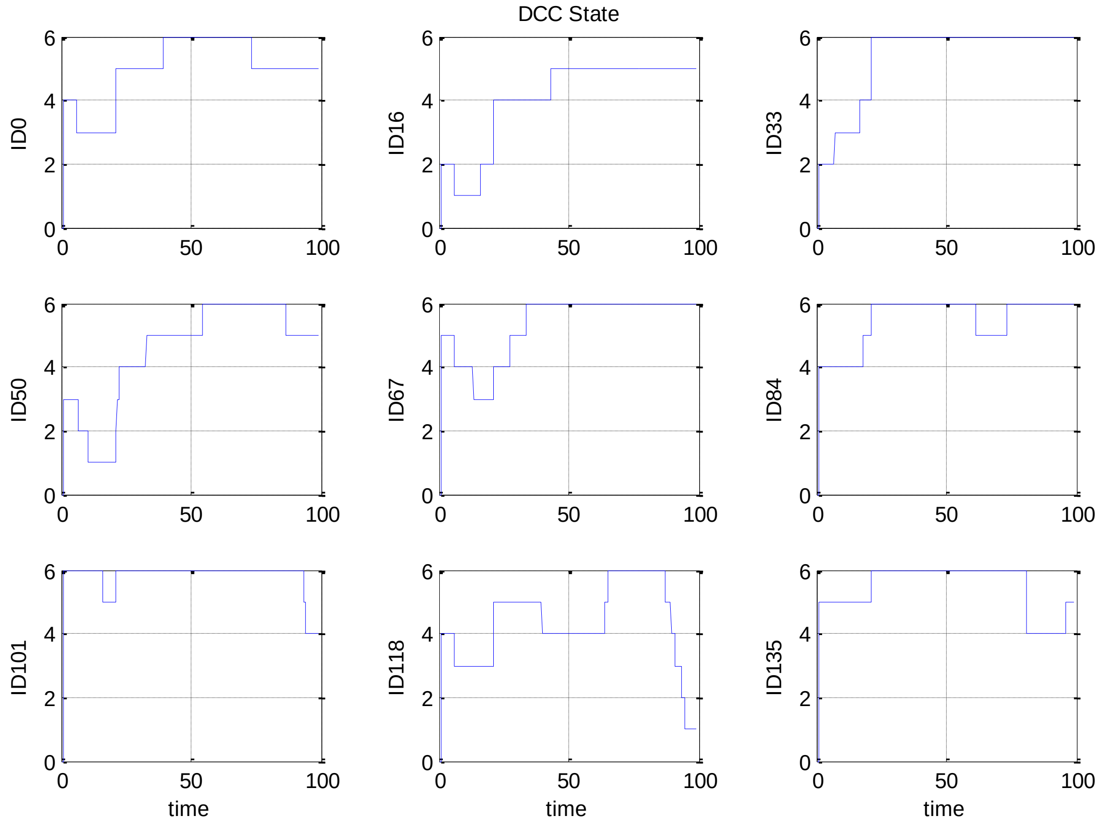


Figure 5-46: DCC state for 9 selected vehicles, DCC variant A, 256 vehicles

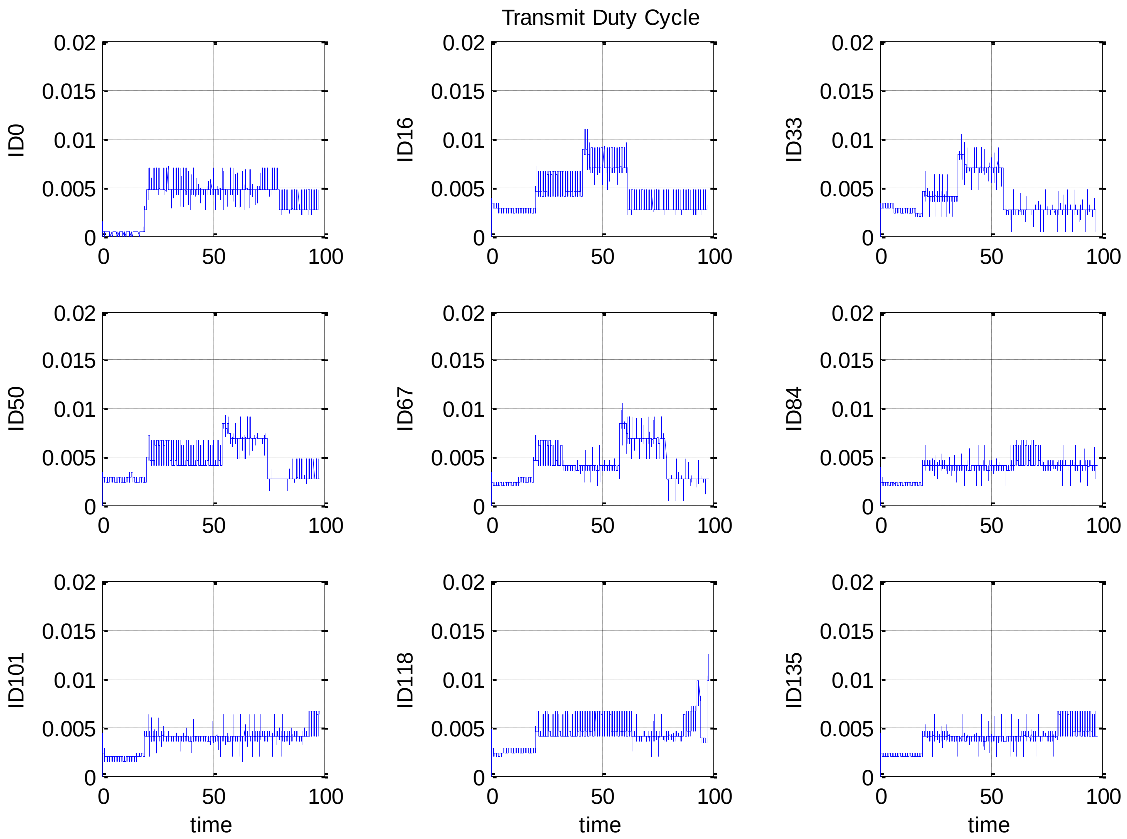


Figure 5-47: Duty cycle for 9 selected vehicles, DCC variant A, 256 vehicles

The mean and maximum duty cycles for all vehicles are shown in Figure 5-48. Once again, two maximum values are given. The green one considers all vehicles positions, while the red one concentrates on the middle of the highway section and skips those value close to the border.

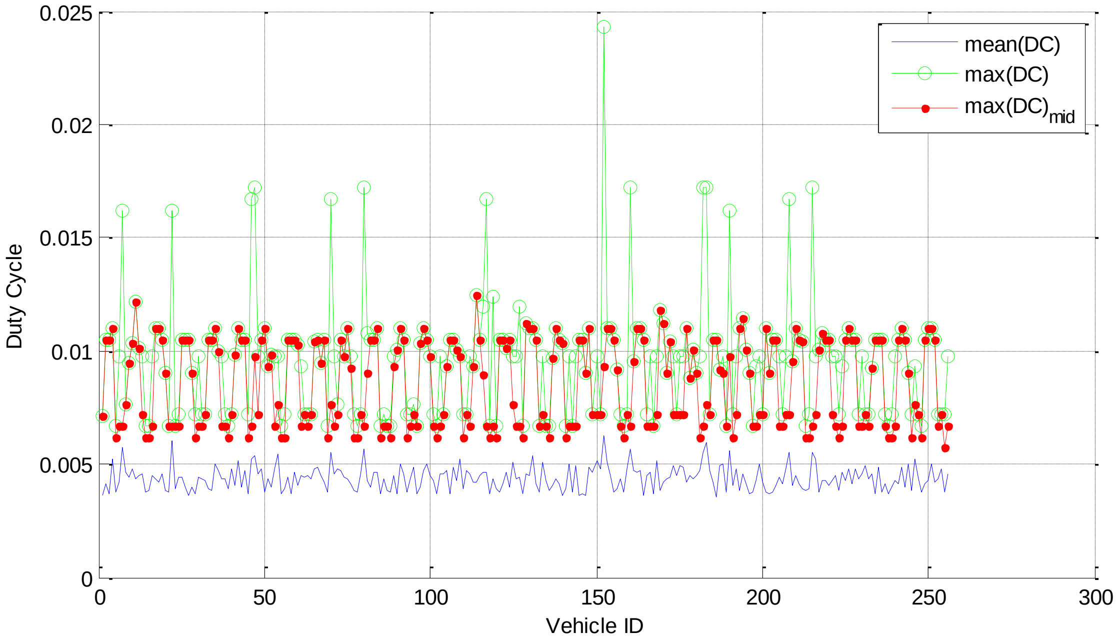


Figure 5-48: Mean and maximum duty cycle, DCC variant A, 256 vehicles

The resulting duty cycles are slightly lower than the results in the scenario with 128 vehicles. The variation in the maximum duty cycle in the middle of the highway section is caused by the additional DP1 transmission for those vehicles driving in the upstream direction. A maximum duty cycle close to 1% is observed. If the duty cycles measured near the highway border are included, the maximum value of one vehicle is close to 2.5% while all the others are well below 2%.

5.2.3.2 Results for DCC variant B

The same simulation is repeated using DCC variant B. An example for the resulting DCC state and channel load is shown in Figure 5-49 for vehicle ID2. The resulting channel load right after the crash seems to be slightly lower compared to the channel load using variant A (see Figure 5-43).

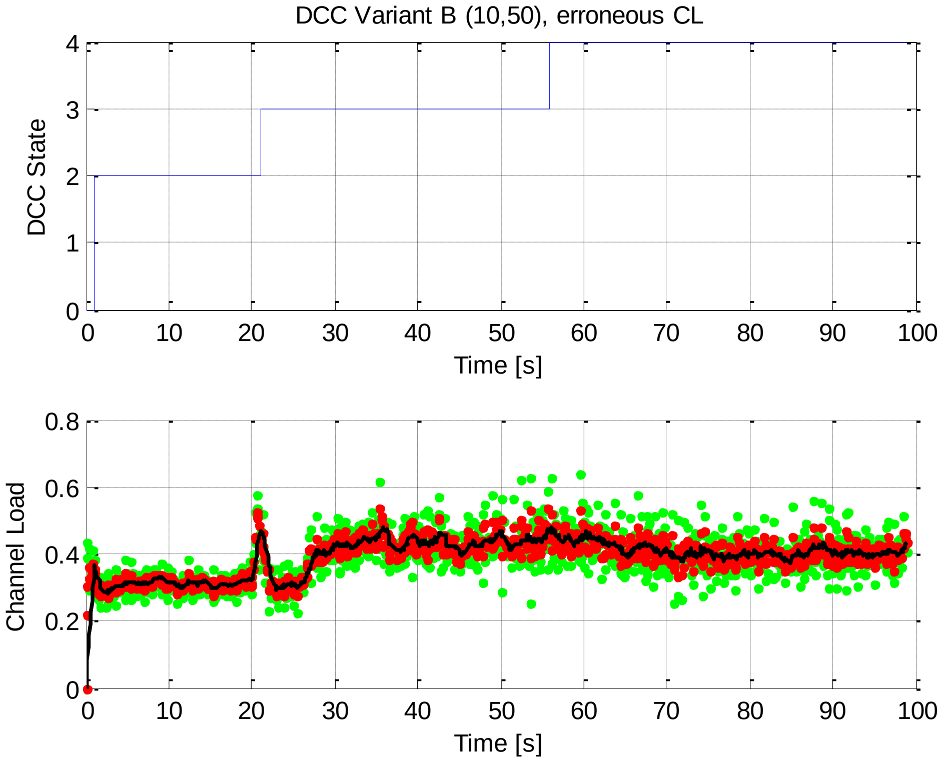


Figure 5-49: DCC state adaptation and measured channel load of vehicle ID2 for DCC variant B with NDL_TimeUp =1s. $NDL\_TimeDown$ =5s, 256 vehicles

Figure 5-50 presents the number of transmitted CAM, DP1, and DP3 packets. Variant B leads to a slightly higher number of CAMs, the same number of DP1, and a significantly lower number of DP3 transmissions for most vehicles, although some of them are transmitting even more DP3 packets than in DCC variant A.

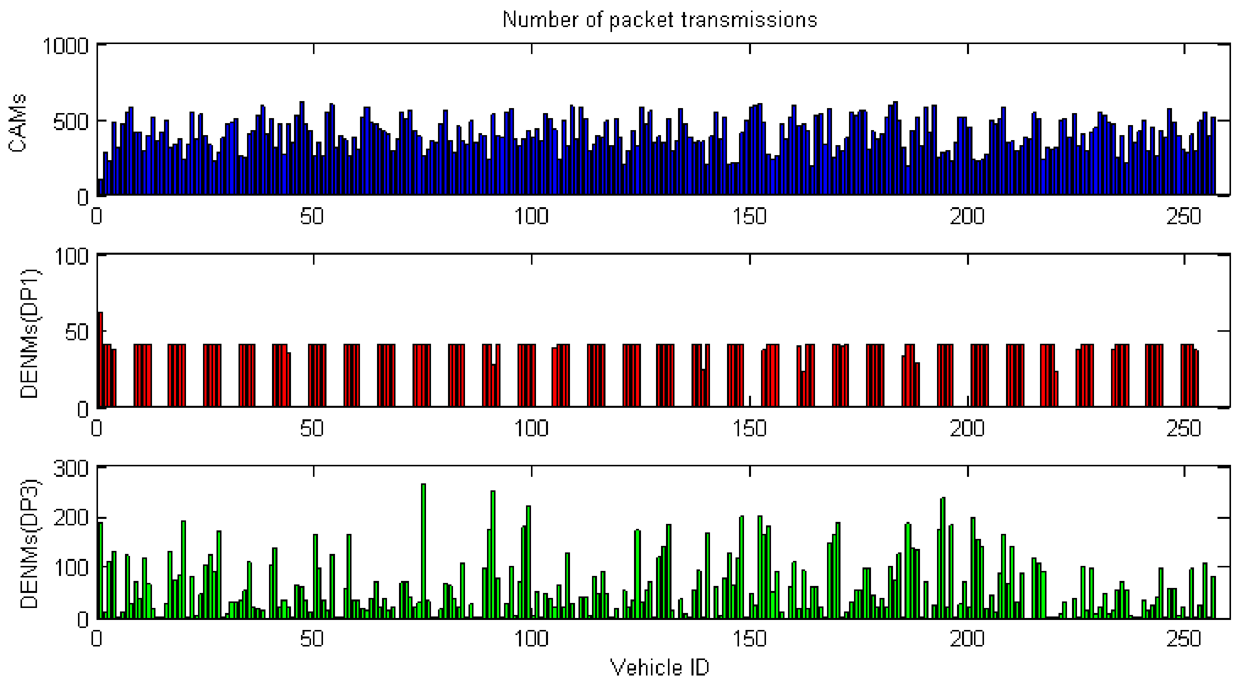


Figure 5-50: Number of transmitted packets as a function of priority, DCC variant B, 256 vehicles

The slightly higher number of CAMs can be confirmed comparing the number of generated CAMs in the facilities layer with the number of CAMs resulting from the CAM generation rule without DCC limitations. The ratio is close to 70% and hence 3% higher than with DCC variant A.

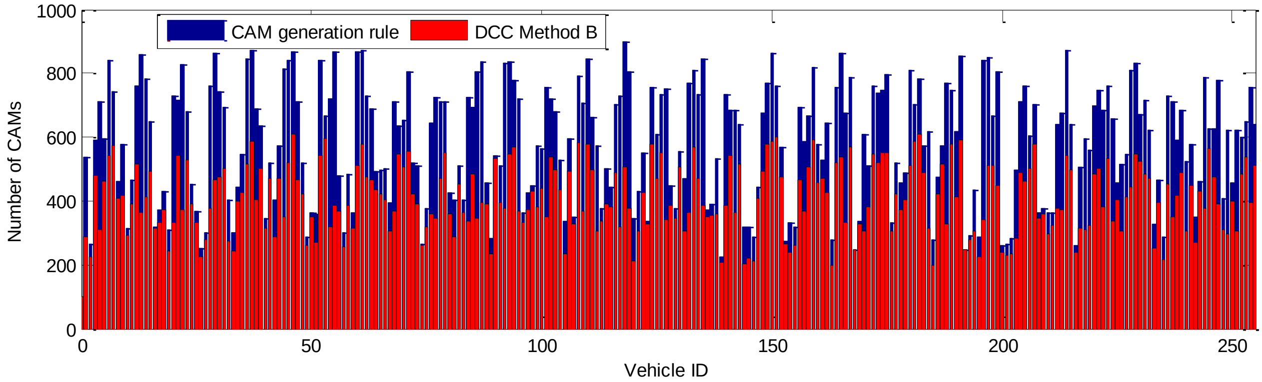


Figure 5-51: Number of CAMs according to CAM generation rule (blue) and at the input of the DCC (red), DCC variant B, 256 vehicles

The number of transmitted and received packets as well as the delays in DCC and MAC are summarized in the table below.

DP1	DP1	CAM	DP3
CAM generation rule		583	
TxRequest	20.2	406	4288
TxPacket	20.1	404	62
RxPacket	2008	37757	4083
$\bar{d}_{DCC}$[s]	0.07	0.14	0.15
$std(d_{DCC})$ [s]	0.04	0.27	0.13
$\hat{d}_{DCC}$[s]	0.15	1.5	0.64
$\bar{d}_{MAC}$[ms]	0.36	0.63	1.10
$std(d_{MAC})$ [ms]	0.47	0.96	1.27
$\hat{d}_{MAC}$[ms]	2.04	7.58	5.49

Table 5-14: DCC variant B, 256 vehicles

As expected the average number of transmitted DP3 packets reduces to 62 compared to 94 using DCC variant A. The delay of DP3 packets in the DCC layer as well as the MAC delays of all packet types are in the same order, although slightly smaller for DCC variant B. Nevertheless DP1 and especially CAMs are significantly delayed in the DCC, which will have impact on the position error as shown later on in section 5.2.3.5.

The next two figures present the DCC state and the duty cycle for the 9 selected vehicles.

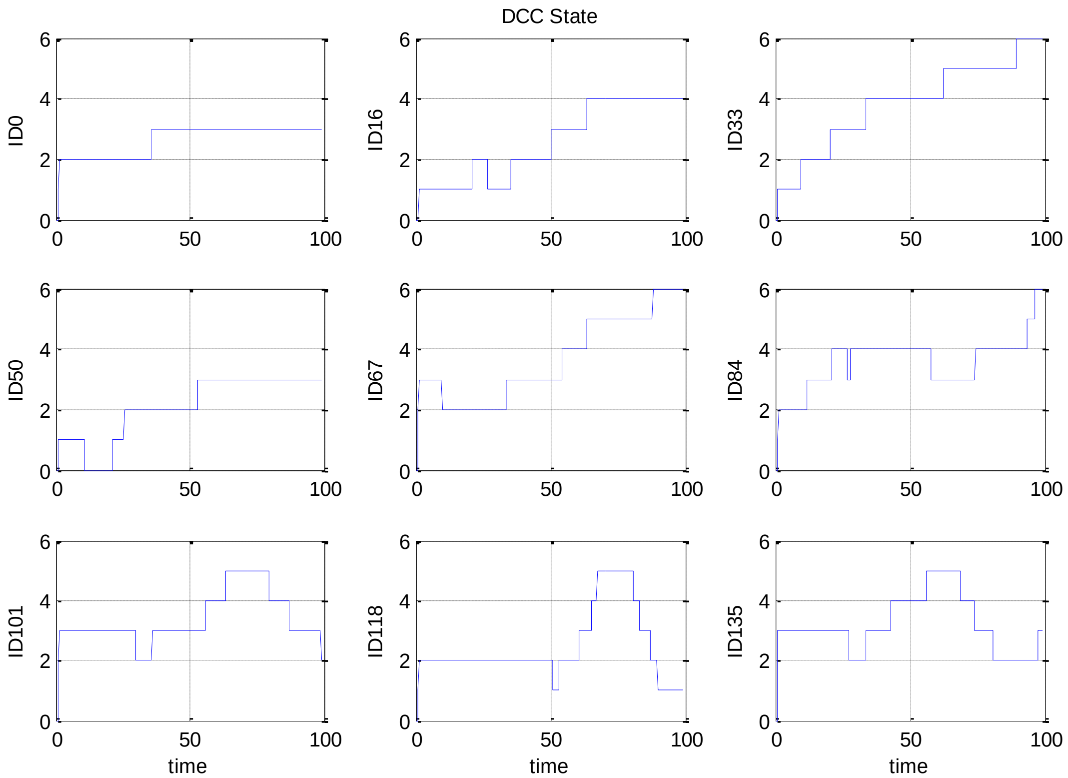


Figure 5-52: DCC state for 9 selected vehicles, DCC variant B, 256 vehicles

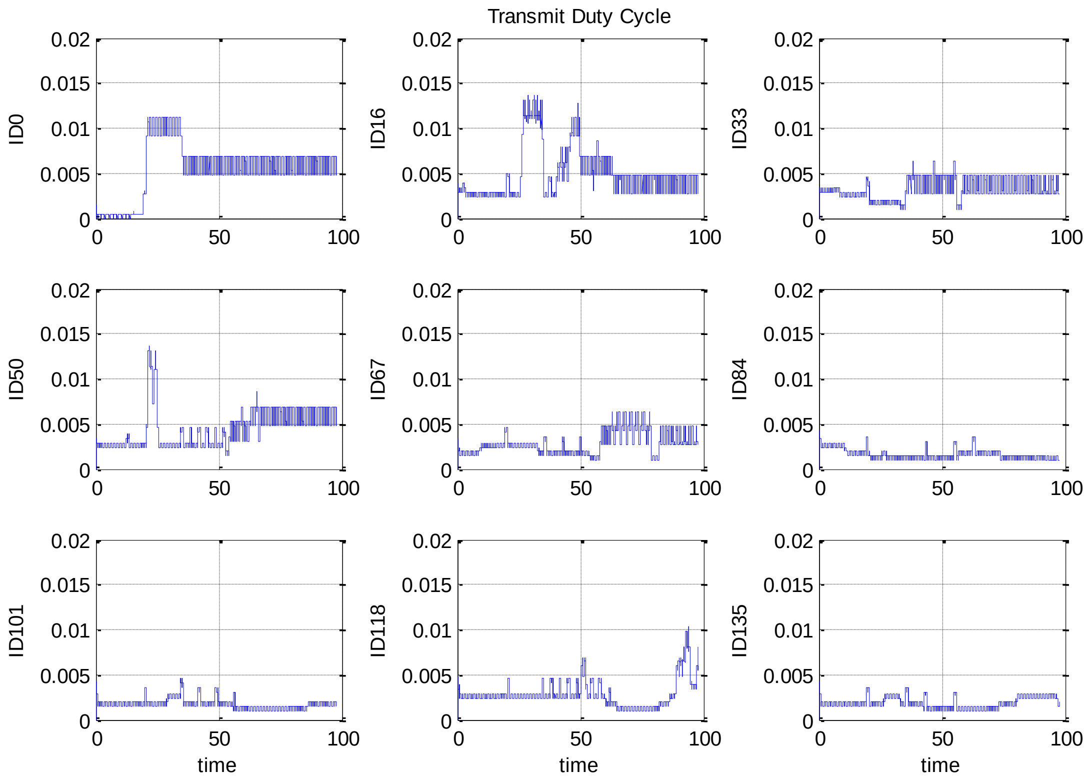


Figure 5-53: Duty cycle for 9 selected vehicles, DCC variant B, 256 vehicles

The variations of the duty cycle over time are larger than using DCC variant A. This can be also observed in Figure 5-54, which shows the mean and maximum duty cycle with and without duty cycle values measured at the border of the highway section. While the maximum duty cycle in the middle of the highway section has been in between 0.6% and 1.1% using DCC variant A, the range is now in between 0.4% and 1.3%. Additionally, peak values at the border of the highway section are often larger than 2%. The reason is that the common packet distance in DCC variant B is smaller than the packet distance of DP3 packets in variant A for the same measured channel load. As there are mainly DP3 packets in the DCC queue, the resulting duty cycle is larger for DCC variant B.

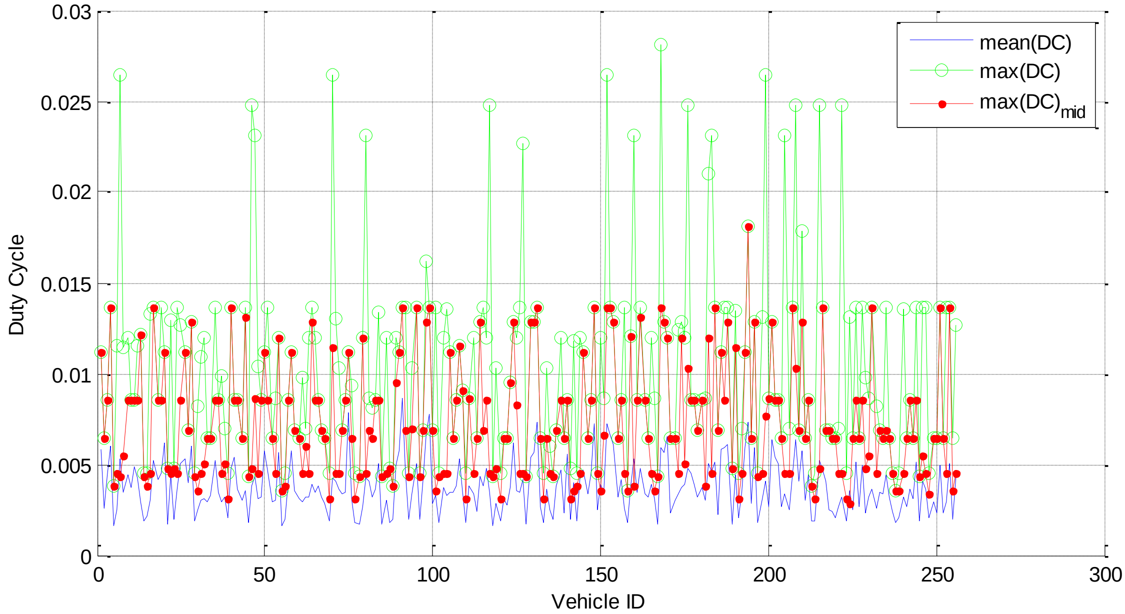


Figure 5-54: Mean and maximum duty cycle, DCC variant B, 256 vehicles

5.2.3.3 Results for modified DCC variant A (DCC variant C without DC limitation)

Using higher channel load thresholds for DCC variant A results in smaller DCC states although the measured channel load is still almost the same compared the original DCC variant A in Figure 5-43.

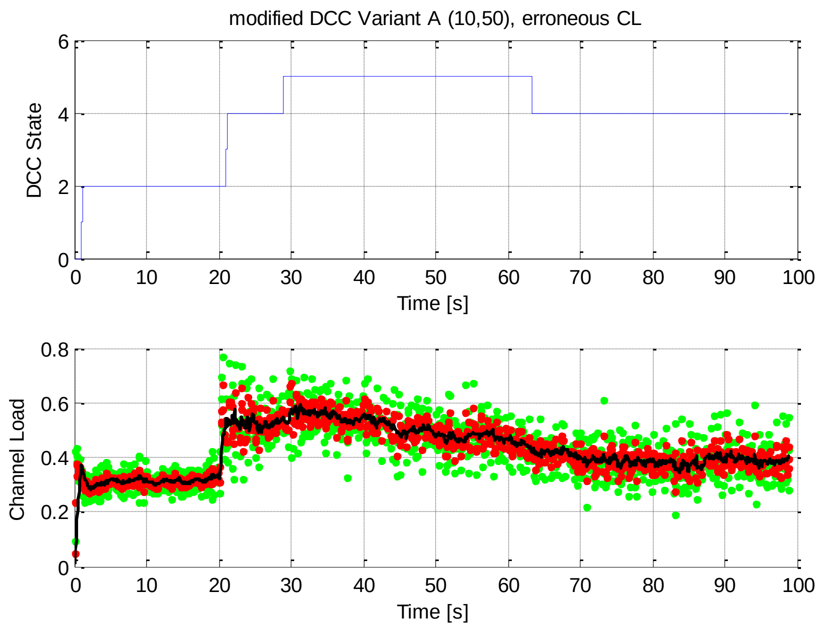


Figure 5-55: DCC state adaptation and measured channel load of vehicle ID2 for modified DCC variant A with NDL_TimeUp =1s, $NDL\_TimeDown$ =5s, 256 vehicles

The transmitted and received packets of all three priority levels are summarised in Table 5-15 together with delays in DCC and MAC layer.

DP1	DP1	CAM	DP3
CAM generation rule		592	
TxRequest	20.2	384.0	5139.3
TxPacket	20.2	384.0	86.3
RxPacket	1903	35859	5990
$\bar{d}_{DCC}$[s]	0	0	0.12
$std(d_{DCC})$ $[s]$	0	0	0.14
$\hat{d}_{DCC}$[s]	0	0	0.92
$\bar{d}_{MAC}$[ms]	0.47	0.86	1.52
$std(d_{MAC})$ [ms]	0.53	1.34	2.22
$\hat{d}_{MAC}$[ms]	2.21	10.62	13.37

Table 5-15: DCC variant A with the new channel thresholds, 256 vehicles

Comparing the results to the outcome of the original DCC variant A in Table 5-13 the number of transmitted CAMs only slightly reduces by 1.8%, while the number of transmitted DP3 packets decreases by 8.7%. Nevertheless, the number of received DP3 packet even increases as the modified DCC version A foresees no transmit power reduction in DCC state *Restrictive*. Hence, the radio range is no longer a function of the DCC state. As a consequence, the impact of DP3 transmissions on the channel load will be higher in the modified DCC variant A, as soon as vehicles enter the highest DCC state. Hence, delays in MAC and DCC are slightly higher than in the original DCC variant A, although the difference is small.

The number transmitted packets within a simulation time of 100 s is shown in Figure 5-56.

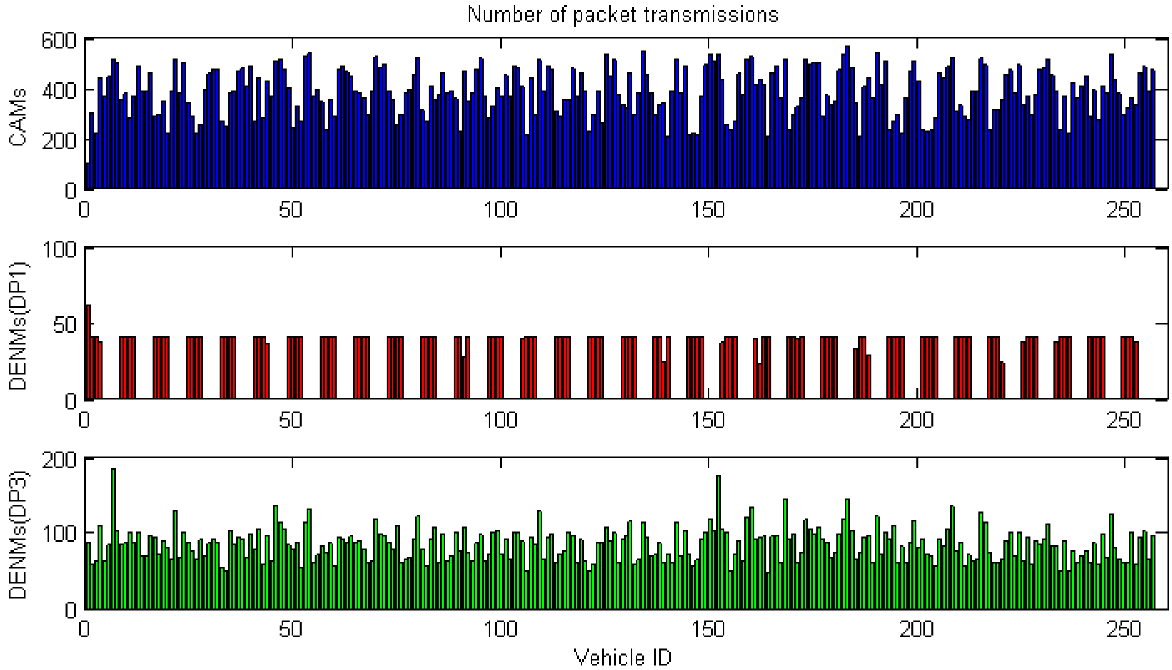


Figure 5-56: Number of transmitted packets as a function of priority, modified DCC variant A, 256 vehicles

DCC states of the selected vehicles are typically smaller than for the original DCC variant A due to the different channel load thresholds (see Figure 5-46). Nevertheless, duty cycles are very similar.

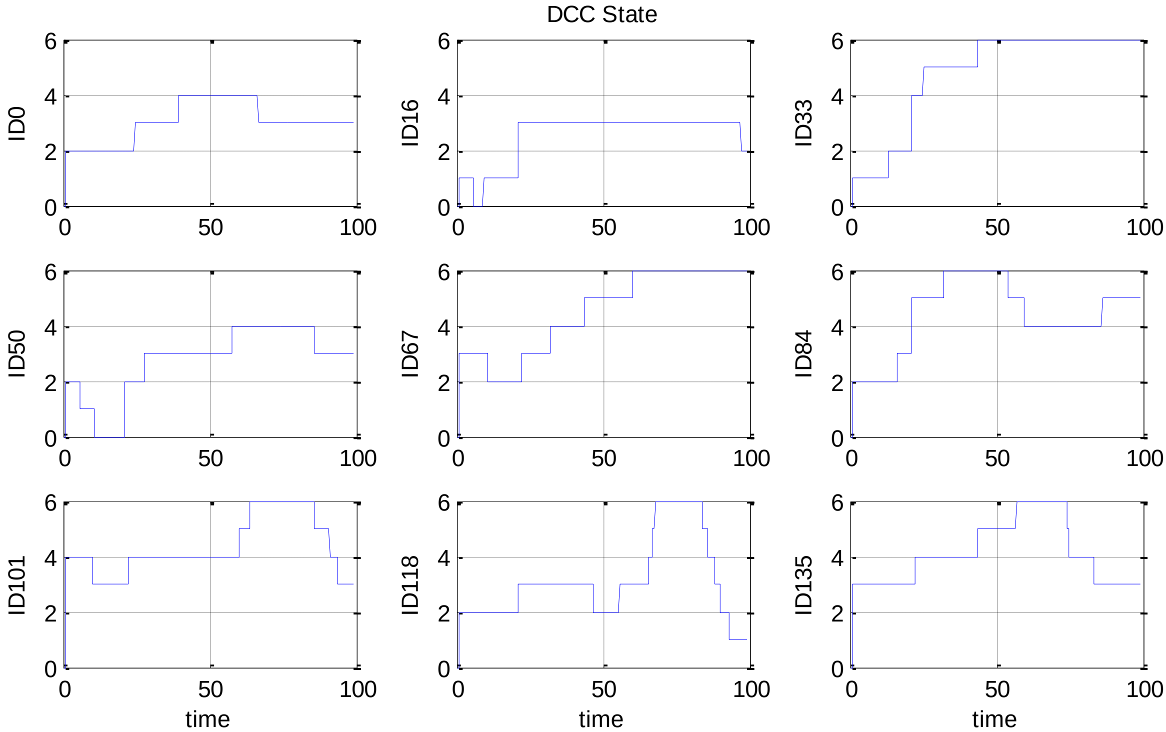


Figure 5-57: DCC state for 9 selected vehicles, modified DCC variant A, 256 vehicles

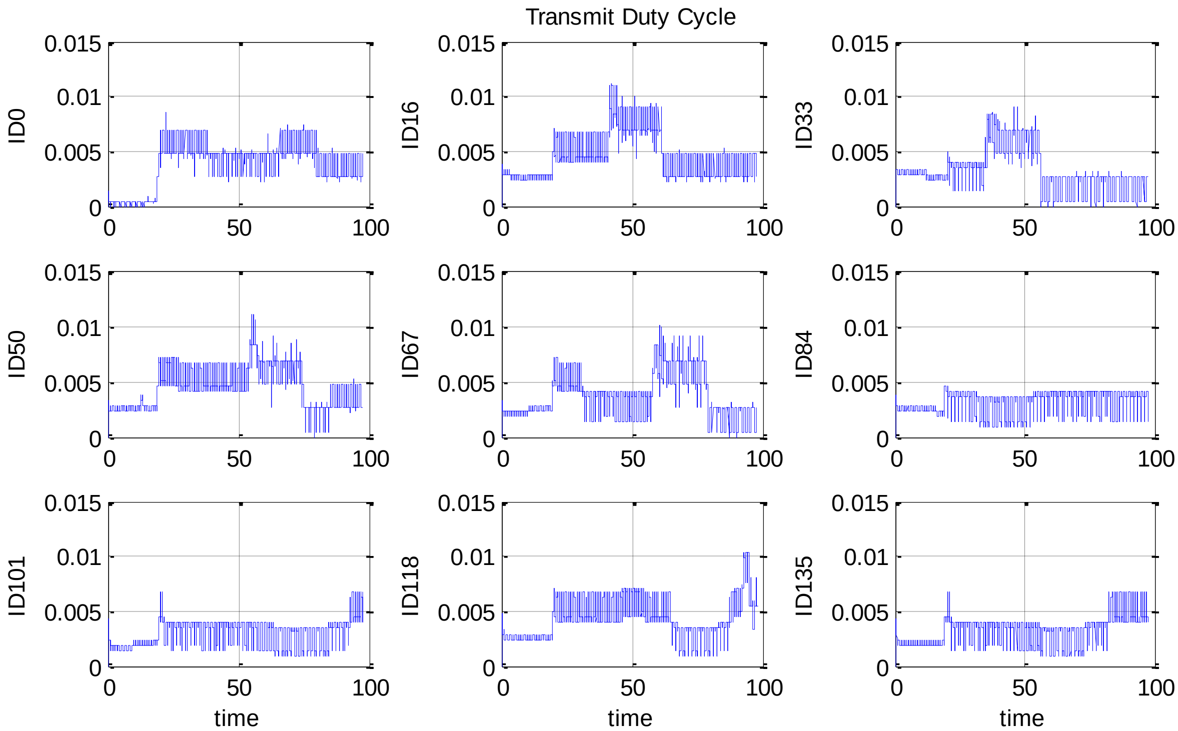


Figure 5-58: Duty cycle for 9 selected vehicles, modified DCC variant A, 256 vehicles

The mean duty cycle shown in Figure 5-59 is again slightly below 0.5%. A small number of vehicles have high peak loads above 2% at the border of the highway sections, while peak duty cycles in the middle of the highway section are only slightly above 1%.

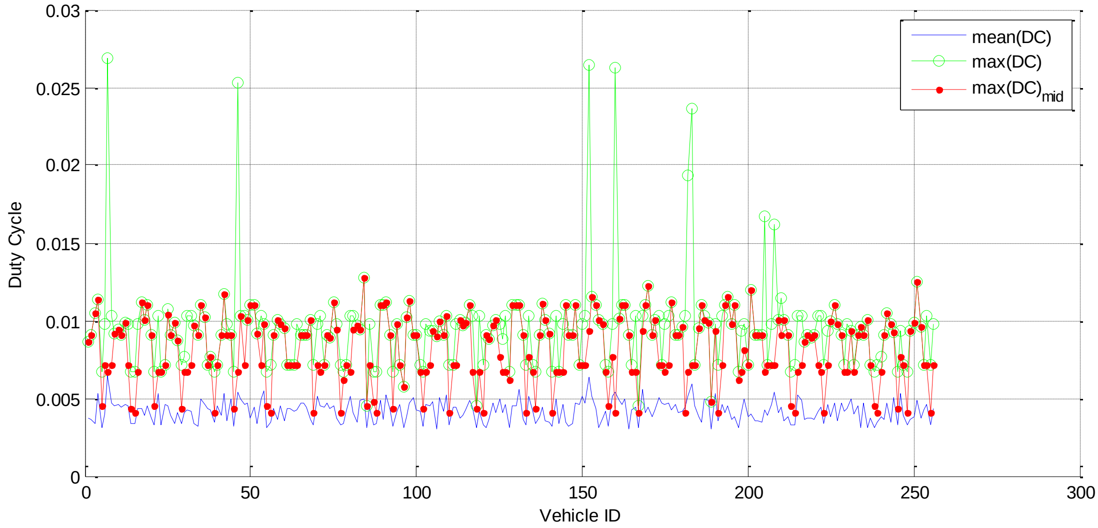


Figure 5-59: Mean and maximum duty cycle, modified DCC variant A, 256 vehicles

5.2.3.4 Results for DCC variant C

Now a duty cycle limitation is added to the transmission rule for DP3 packets. Nevertheless, the DCC state and the measured channel load of vehicle ID2 are almost identical to the results of the modified DCC variant A in Figure 5-55.

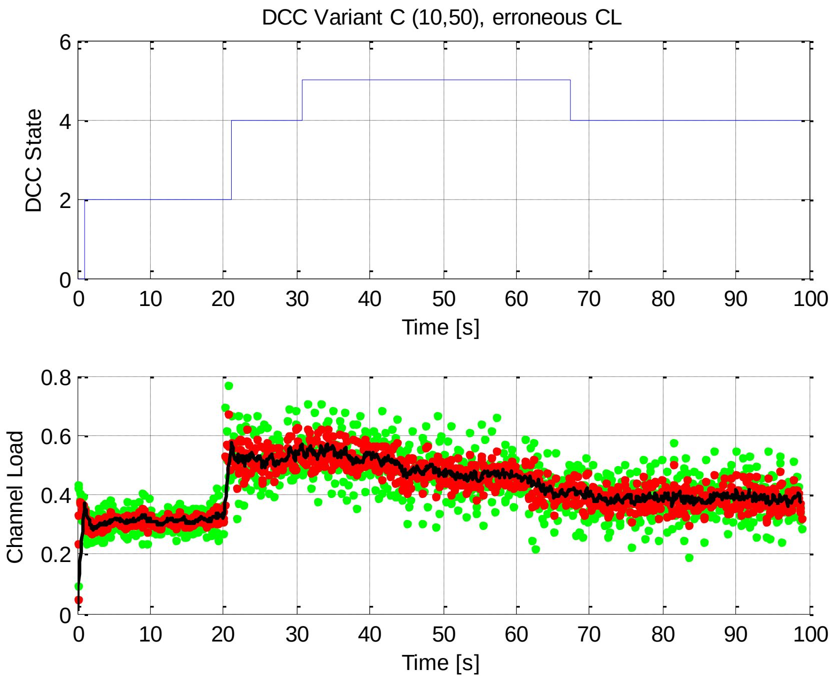


Figure 5-60: DCC state adaptation and measured channel load of vehicle ID2 for DCC variant C with NDL_TimeUp =1s. $NDL\_TimeDown$ =5s, 256 vehicles

The same holds for the number of transmitted CAMs and DP1 packets. Only the number of DP3 packet transmissions seems to be smaller comparing the results in Figure 5-61 and Figure 5-56 for the modified DCC variant A.

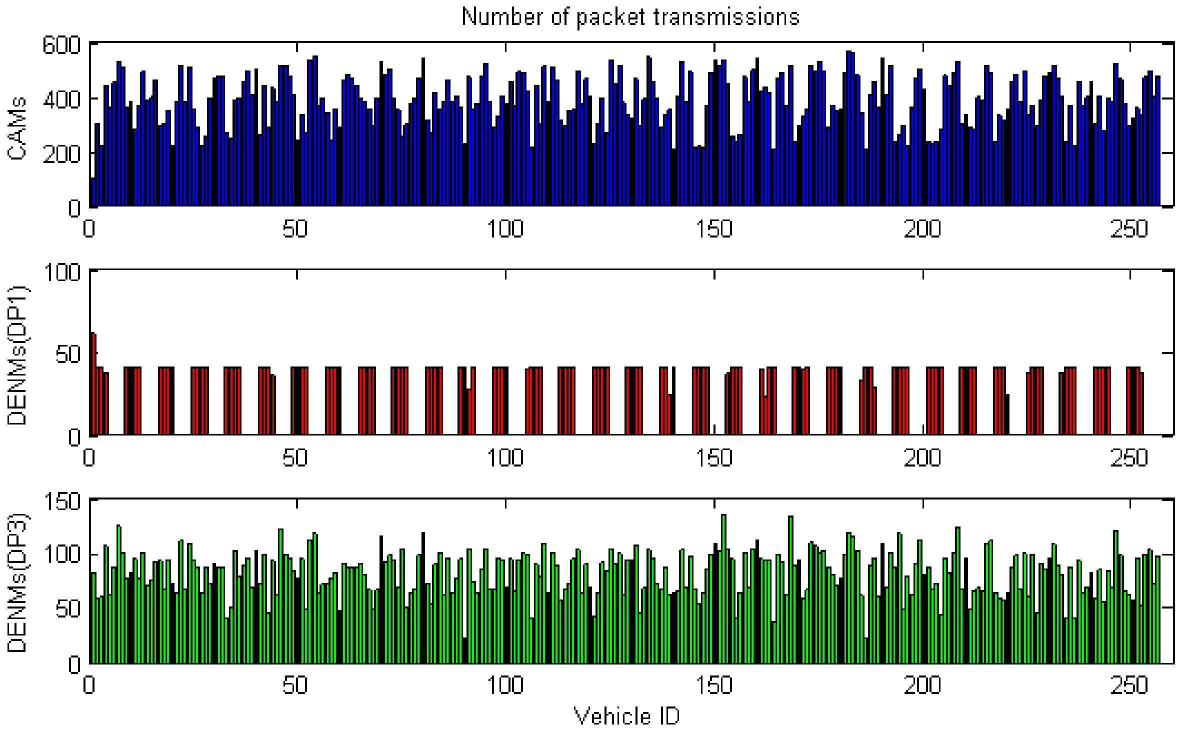


Figure 5-61: Number of transmitted packets as a function of priority, DCC variant C, 256 vehicles

This is confirmed by the average number of transmitted packets per vehicle summarised in Table 5-16. The number of DP3 packets has been reduced by 4.7% compared to the results of the modified DCC variant A.

DP1	DP1	CAM	DP3
CAM generation rule		583	
TxRequest	20.2	386.9	5031.9
TxPacket	20.2	386.9	82.4
RxPacket	1884	36290	5782
$\bar{d}_{DCC}$[s]	0	0	0.12
$std(d_{DCC})$ $[s]$	0	0	0.16
$\hat{d}_{DCC}$[s]	0	0	1.03
$\bar{d}_{MAC}$[ms]	0.51	0.84	1.67
$std(d_{MAC})$ [ms]	0.55	1.36	2.46
$\hat{d}_{MAC}$[ms]	2.34	11.17	14.36

Table 5-16: DCC variant C, 256 vehicles

DCC state and duty cycle of the 9 selected vehicles are shown in Figure 5-62 and Figure 5-63, respectively.

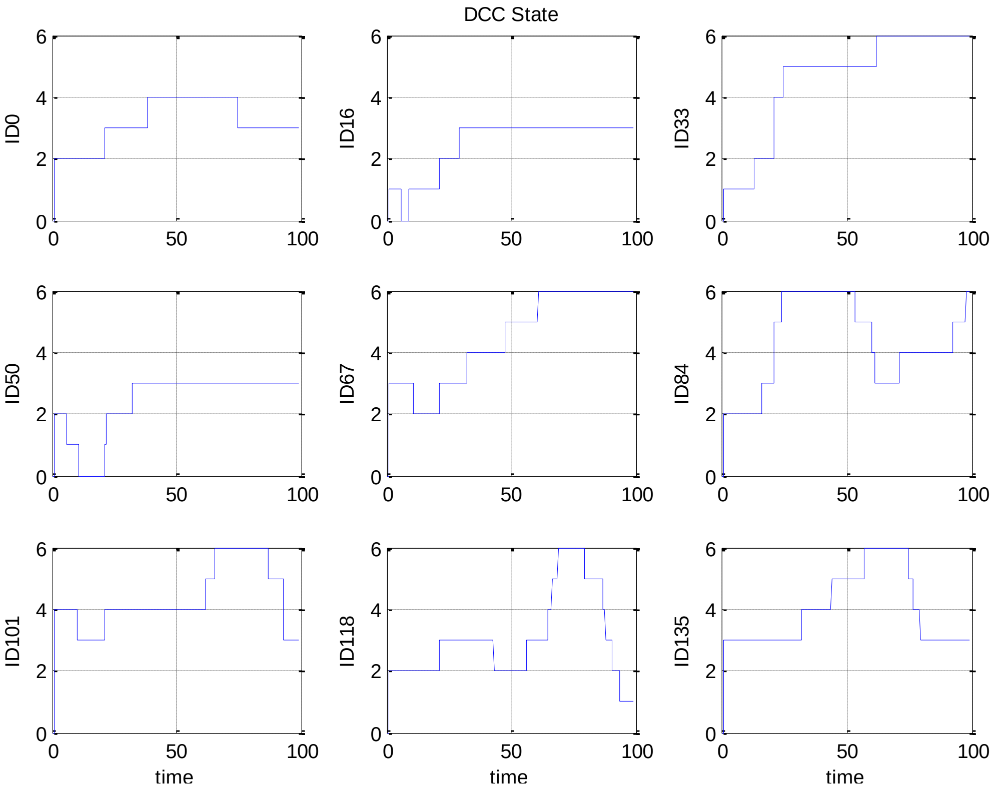


Figure 5-62: DCC State for 9 selected vehicles, DCC variant C, 256 vehicles

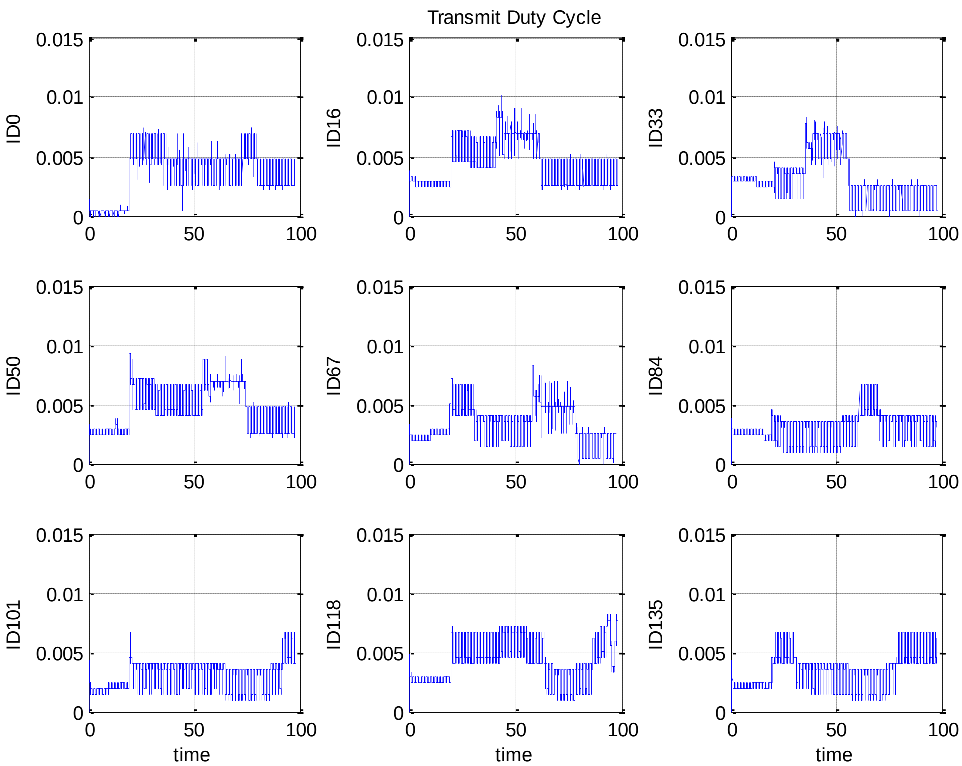


Figure 5-63: Duty cycle for 9 selected vehicles, DCC variant C, 256 vehicles

The effect of duty cycle limitations becomes visible comparing the peak values for all vehicles at all positions. Due to the duty cycle limitation for DP3 packets the peak duty cycles are never significantly higher than 1%. All peaks above 2% which has been observed in the modified DCC version A are avoided.

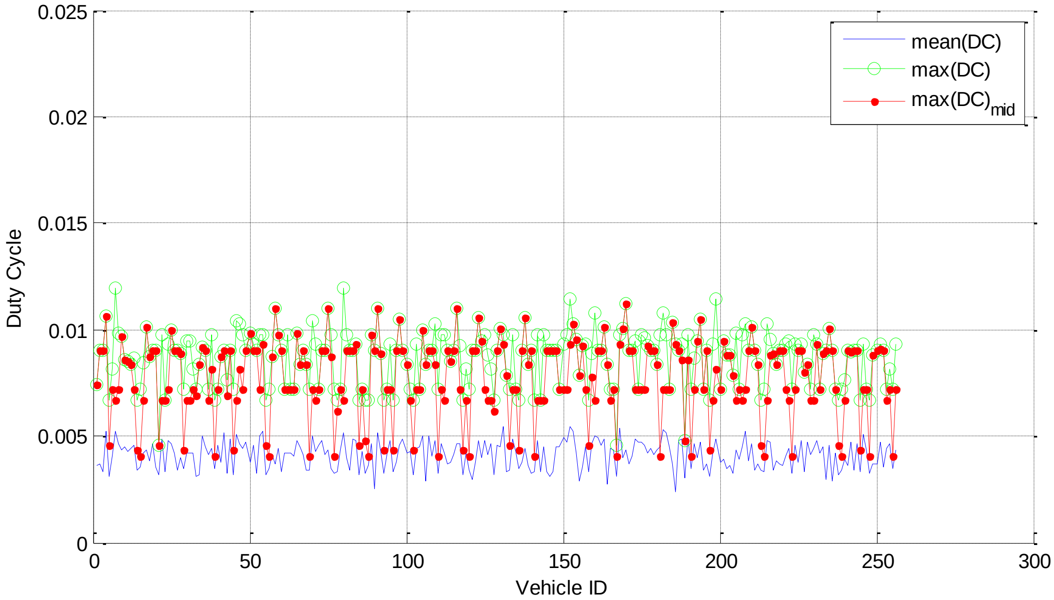


Figure 5-64: Mean and maximum duty cycle, DCC variant C, 256 vehicles

5.2.3.5 Position Error

The position error based on CAM packets which are generated according to the CAM generation rule is again close to 4 m as shown on the left side of Figure 5-65. In case DCC variant A is considered, the position error based on the transmitted CAM packets takes values up to 10 m as indicated by the plot on the right side.

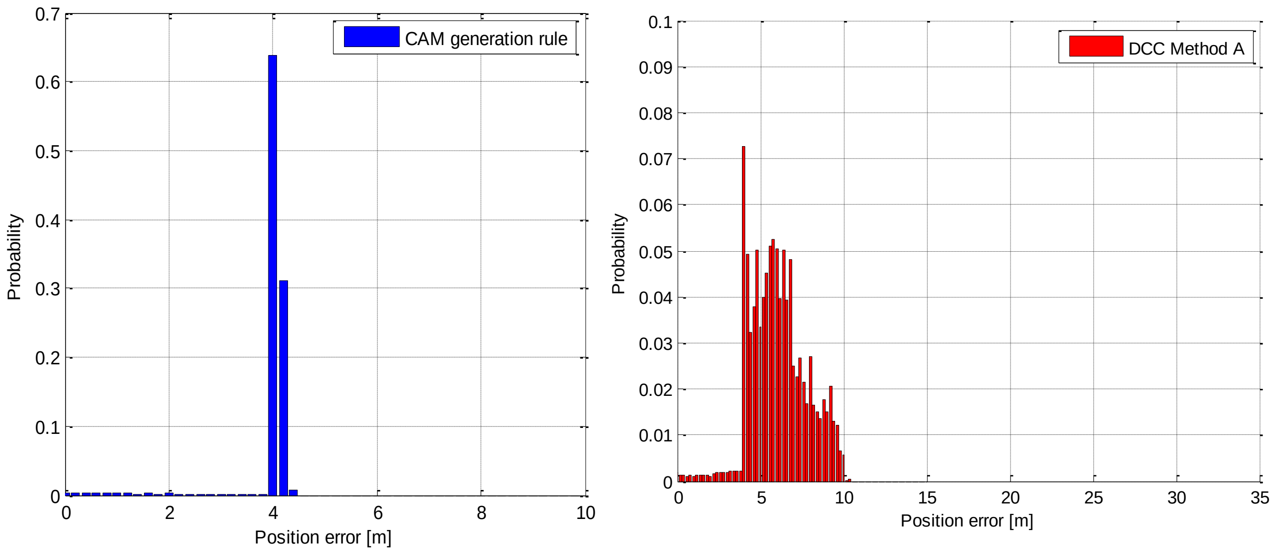


Figure 5-65: Probability of position error for using CAM generation rule and no DCC limitations (left) and DCC variant A (right) based on transmitted CAM packets, 256 vehicles

The same analysis is done for DCC variant B and the results are shown on the left side of Figure 5-66 for a CAM queue length of 5 packets and on the right side for a CAM queue length of 1 packet. The probability of a position error close to 4 m is significantly higher than with DCC variant A. The small errors are obtained during the first 20 s of simulation time prior to the crash. The majority of the vehicles are in DCC state *Active2* with a minimum packet distance of 180 ms. As only CAMs are transmitted during this phase, this corresponds to the CAM repetition interval. In DCC variant A vehicles are often in state *Active4* corresponding to a CAM interval of 204 ms. Nevertheless, the performance of DCC variant B is significantly worse after the crash. Position errors even above 20 m are observed.

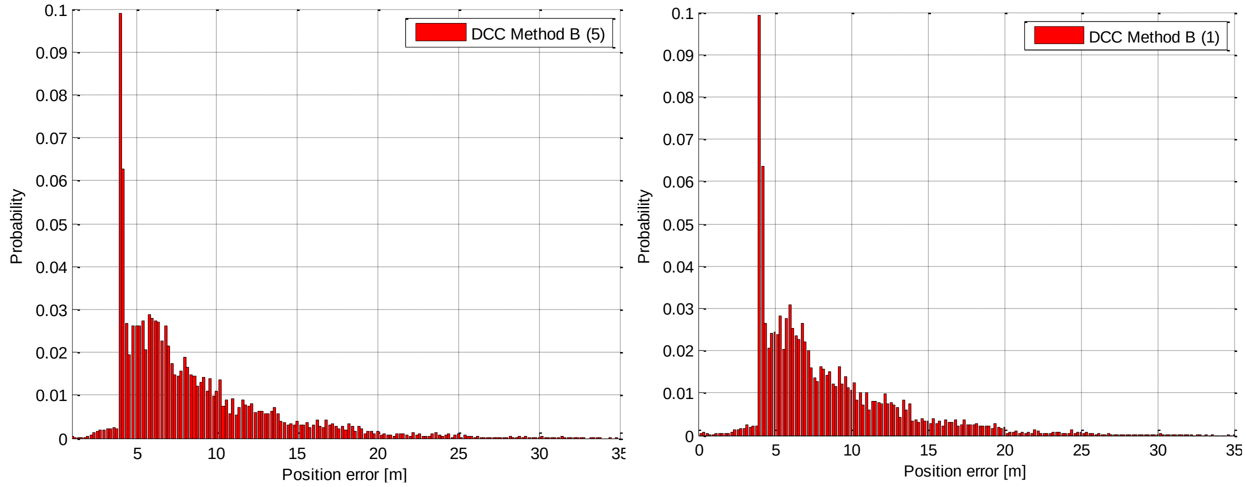


Figure 5-66: Probability of position error for DCC variant B with a CAM queue length of 5 (left) 1 packet (right) based on transmitted CAM packets, 256 vehicles

Using the modified DCC version A improves the channel error as shown of the left side of Figure 5-67, although a very few errors are above 10 m. The original DCC version A performs slightly better as it allows for shorter CAM packet distance for channel loads above 42%. The performance of DCC variant C is almost identical to the performance of the modified DCC variant A as shown of the right side of the figure below.

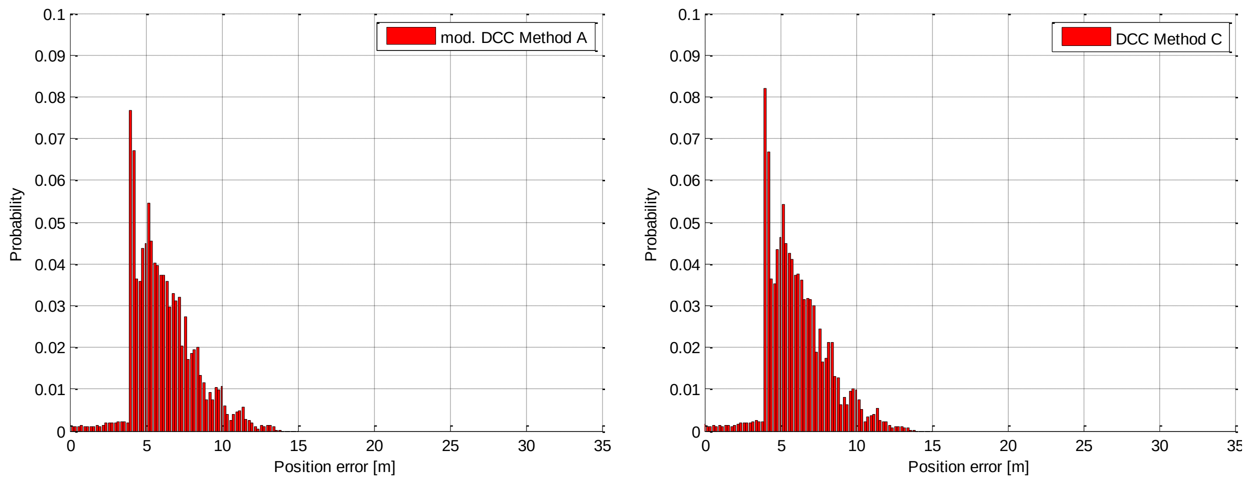


Figure 5-67: Probability of position error for modified DCC variant A (left) and DCC variant C (right) based on transmitted CAM packets, 256 vehicles

In summary, mean, maximum, and standard deviation shown in Table 5-17 are significantly higher for DCC variant B compared to DCC variant A and C. This is true for both versions of the DCC variant B implementation, the original one with a DP2 queue length of 5 packets and a modified version with a queue length of only one packet.

Position Error	Variant A	Variant B(5)	Variant B(1)	mod. Variant A	Variant C
mean	6.15	8.33	8.36	6.28	6.23
standard deviation	1.71	4.62	4.54	2.3	2.00
max	10.57	34.91	35.51	13.98	13.98

Table 5-17: Position errors for the different DCC variants in a highway scenario with 256vehicles

Finally the position error is calculated based on the received CAM packets. If packet losses are included, the position error increases, so that large position errors above 20 m are observed for all DCC variants. Nevertheless, the majority of the errors are significantly smaller in DCC variant A and C, while DCC variant B has a significantly higher probability for position errors above 10 m for both DCC queue length settings.

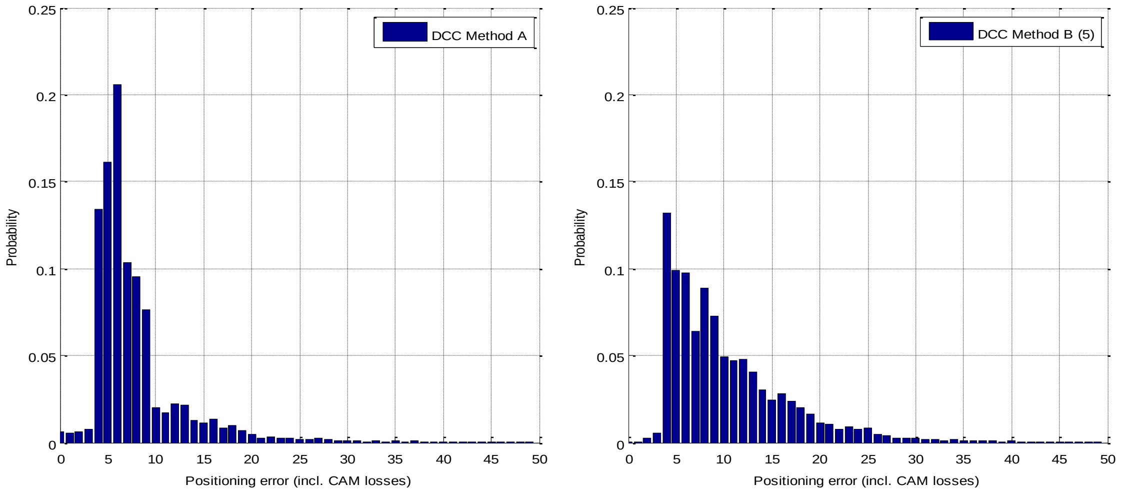


Figure 5-68: Probability of position error for DCC variant A (left) and DCC variant B with a CAM queue length of 5 (right) based on received CAM packets, 256 vehicles

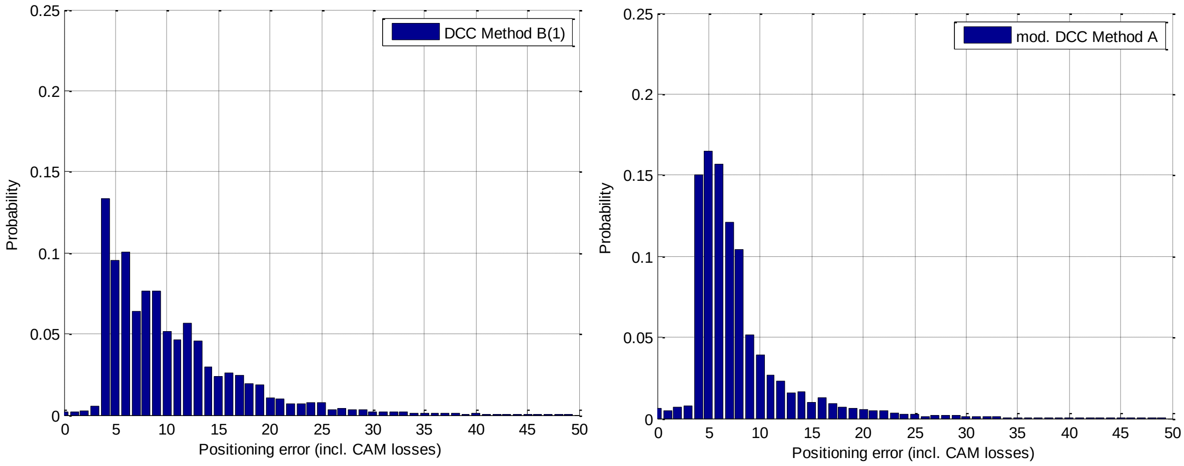


Figure 5-69: Probability of position error for DCC variant B with a CAM queue length of 1 (left) and the modified DCC variant A (right) based on received CAM packets, 256 vehicles

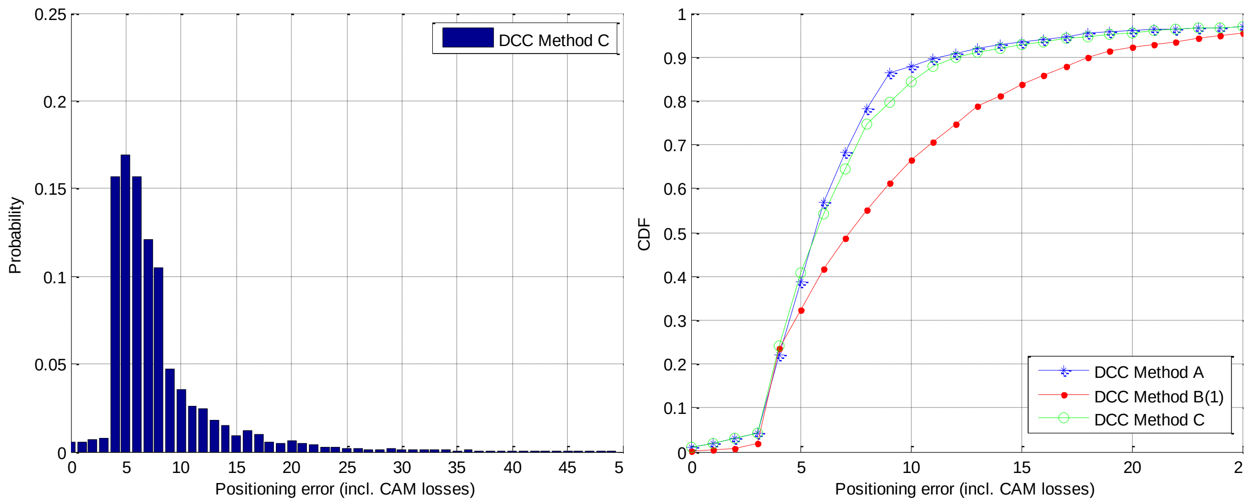


Figure 5-70: Probability of position error for DCC variant C, 256 vehicles

The cumulative distribution function shown on the right side of Figure 5-70 proofs that 90% of the position errors in DCC variant A and C are below 12 m, while DCC variant B results in errors up to 18 m.

5.2.3.6 Packet collision rates

The higher number of vehicles results in an increase of the packet collision rate during the pre-crash phase from 12% in the scenario with 128 vehicles to 19% in the scenario with 256 vehicles for DCC variant A or C, respectively. DCC variant B again has a slightly higher collision rate of 20% due to the shorter CAM transmission intervals in the pre-crash phase.

Packet Collision Rate	variant A	variant B (5) / (1)	mod. variant A / variant C
mean	0.186	0.204	0.187
median	0.189	0.202	0.187
standard deviation	0.067	0.072	0.067

Table 5-18: Packet collision rates in the pre-crash phase, 256 vehicles

During the post-crash phase the packet collision rate increases to 25% for DCC variant B and 29% for DCC variant A and C. The collisions rate for the latter is higher due to the significantly higher number of DP3 packets transmission. The duty cycle limitation for DP3 packets in DCC variant C has only a small impact on the total number of DP3 packets, so there is only a small difference of 0.5% with regards to the modified DCC variant A.

Packet Collision Rate	variant A	variant B (5)	variant B (1)	mod. variant A	variant C
mean	0.295	0.255	0.251	0.294	0.29
median	0.266	0.237	0.236	0.266	0.26
standard deviation	0.087	0.079	0.077	0.088	0.088

Table 5-19: Packet collision rates in the post-crash phase, 256 vehicles

Comparing the packet collision rates as a function of the filtered channel load shows almost identical results for the three different DCC variants also for the higher number of vehicles.

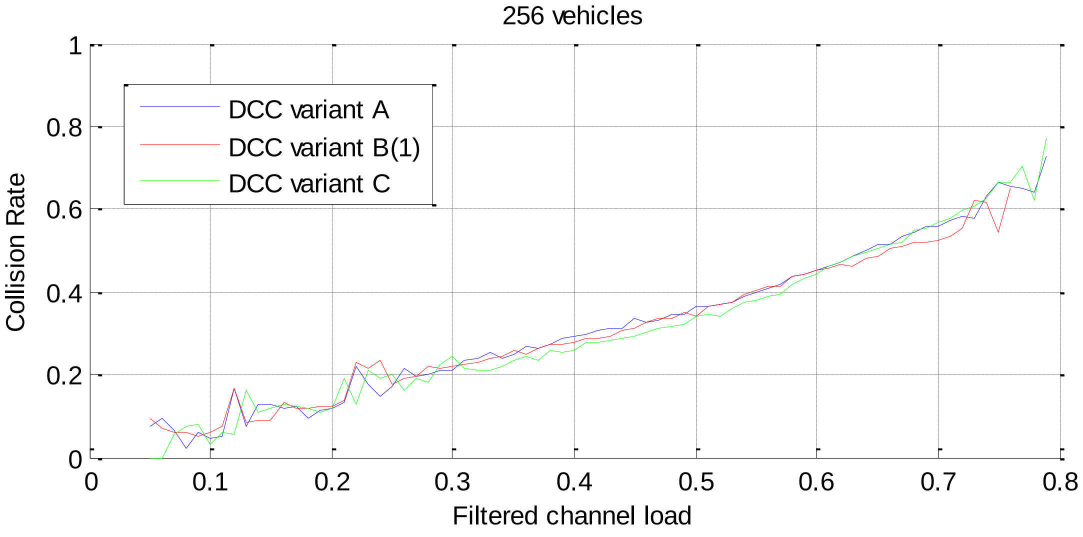
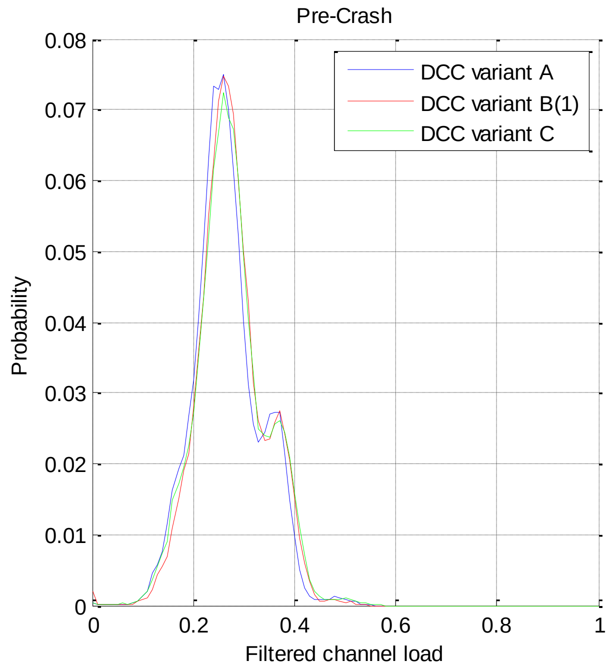


Figure 5-71: Collision rate as a function of filtered channel load for 256 vehicles

The distribution of filtered channel loads during the pre-crash phase is almost identical for the three DCC variants as shown on the left side of Figure 5-72. After the crash, DCC variant C tends to slightly higher channel loads.



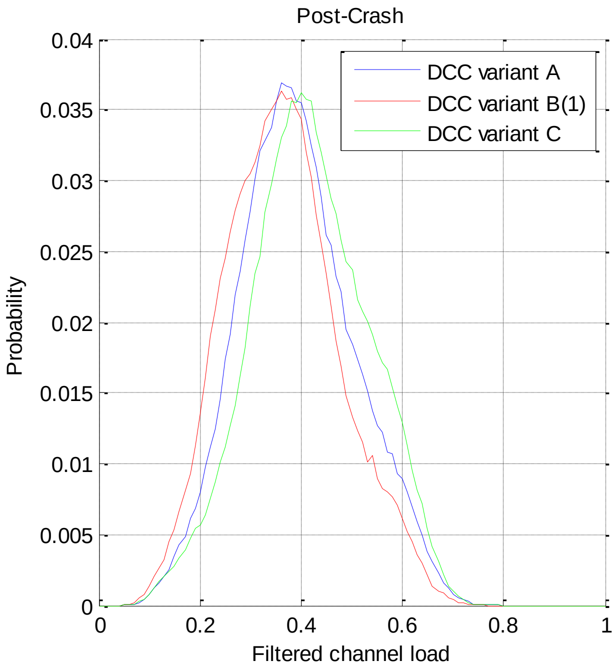


Figure 5-72: Probability function of the filtered channel load during pre-crash and post-crash phase, 256 vehicles

Mean value and standard deviation of packet collision rate are listed for the pre-crash and post-crash phase in Table 5-20. The mean value for DCC variant C during the post-crash phase is 2.5% higher compared to DCC variant A and 5.4% higher compared to DCC variant B. The standard deviations are almost identical.

	Filtered channel load	variant A	variant B (1)	variant C
Pre-crash	mean	27.2 %	28.0 %	28.1%
	standard deviation	6.6 %	6.5 %	6.8 %
Post-crash	mean	39.7 %	36.8 %	42.2 %
	standard deviation	11.3 %	11.2 %	11.4 %

Table 5-20: Packet collision rates in the post-crash phase, 256 vehicles

5.2.4 Simulation results for the highway scenario with 512 vehicles

The positions of the nine selected vehicles are shown in Figure 5-73.

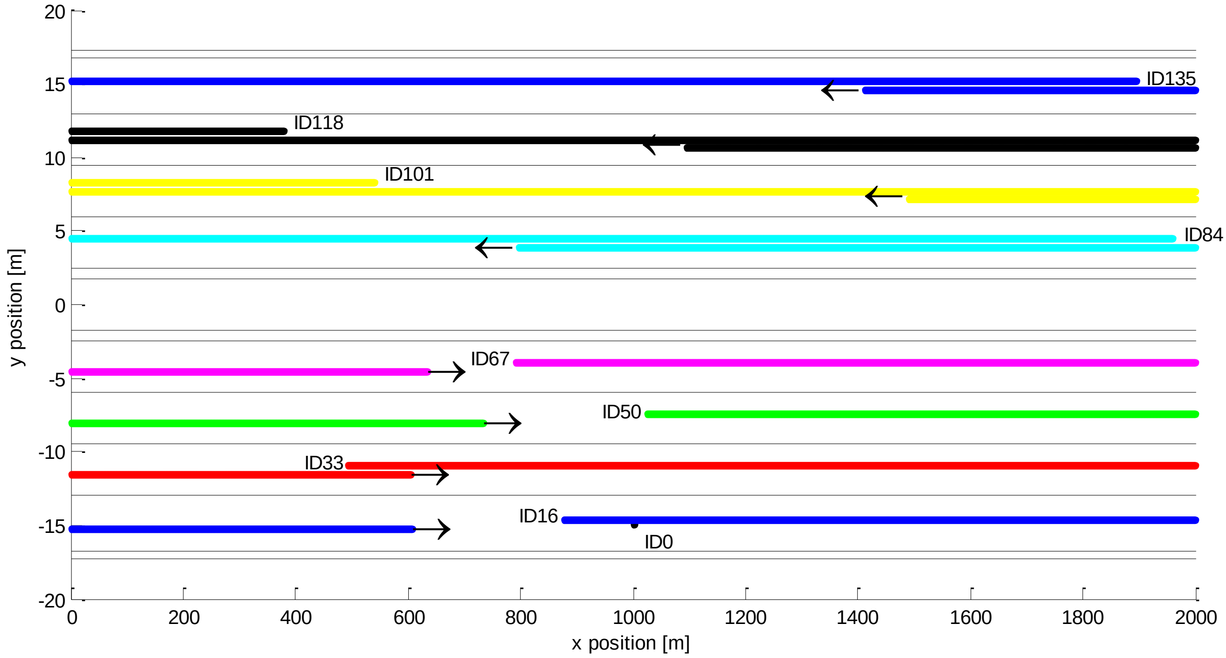


Figure 5-73: Traces of 9 selected vehicles, highway scenario with 512 vehicles

5.2.4.1 Results for DCC variant A

The DCC state adaptation and the measured channel load are exemplarily shown for vehicle ID0 in Figure 5-74. The high traffic on the channel causes the DCC layer to stay in *Restrictive* state right after the crash.

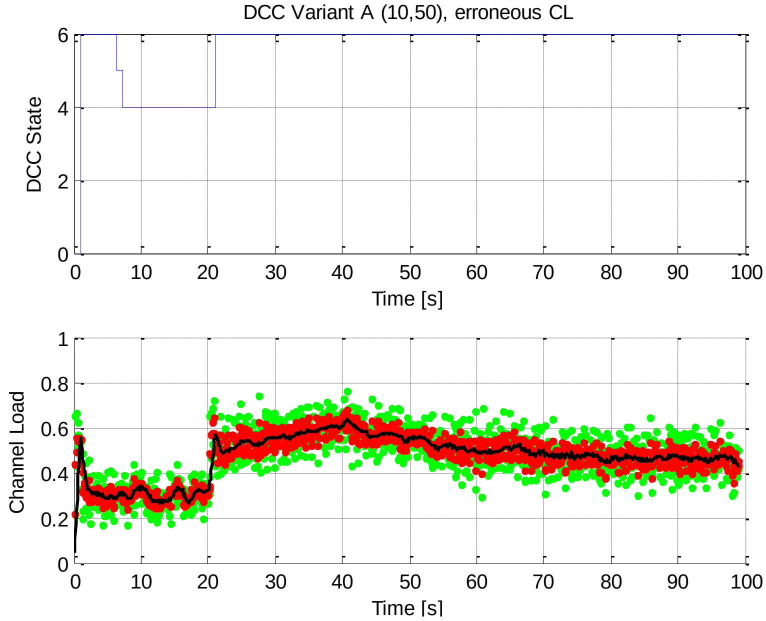


Figure 5-74: DCC state adaptation and measured channel load of vehicle ID0 for DCC variant A with NDL_TimeUp =1s, $NDL\_TimeDown$ =5s, 512 vehicles

Looking at the number of transmitted packets for all three priority levels, the number of CAMs seems to be slightly lower than observed in the simulations with lower vehicle densities, while the number of DP1 transmissions is still identical.

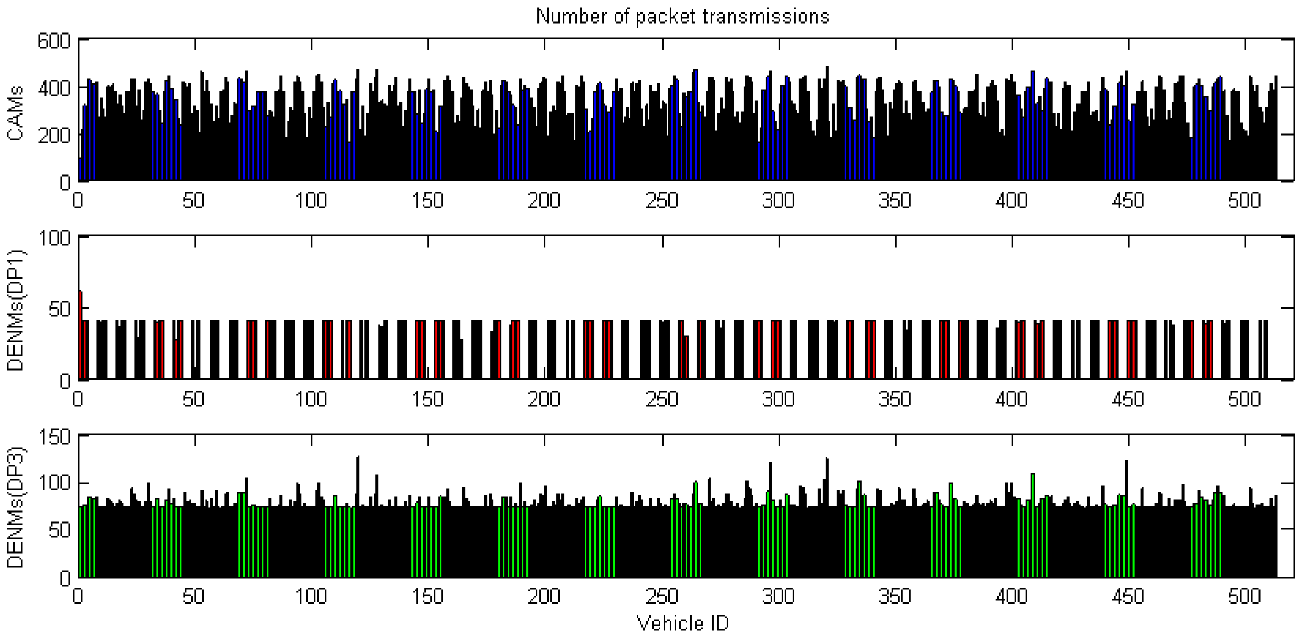


Figure 5-75: Number of transmitted packets as a function of priority, DCC variant A, 512 vehicles

While the number of CAMs varies according to the vehicle speed and DP1 packets are only transmitted by vehicles moving the upstream direction towards the traffic jam, the number of DP3 packets is quite similar for all vehicles.

According to the results summarised in Table 5-21, the number of CAMs corresponds to 62% of the CAMs which would have been generated according to the CAM generation rule. Additionally, the average number of transmitted DP3 packets reduces from 94.5 in the scenario with 256 vehicles to 84.3. DCC delays for DP3 packets and MAC delay for all packets slightly worsens compared to the previous simulations with smaller number of vehicles.

DP1	DP1	CAM	DP3
CAM generation rule		566.4	
TxRequest	19.7	352.3	4443.4
TxPacket	19.7	352.3	84.3
RxPacket	2138	43333	4111
$\bar{d}_{DCC}$[s]	0	0	0.16
$std(d_{DCC})$ [s]	0	0	0.18
$\hat{d}_{DCC}$[s]	0	0	1.07
$\bar{d}_{MAC}$[ms]	0.61	1.18	2.43
$std(d_{MAC})$ [ms]	0.59	1.75	2.78
$\hat{d}_{MAC}$[ms]	2.45	13.24	14.75

Table 5-21: DCC variant A, 512 vehicles

DCC state adaptations and measured duty cycles for the 9 selected vehicles are shown in Figure 5-76 and Figure 5-77, respectively. Due to the higher channel states the duty cycles are smaller than in the scenarios with lower number of vehicles. Even the highest values are in the order of 1% for all 9 examples.

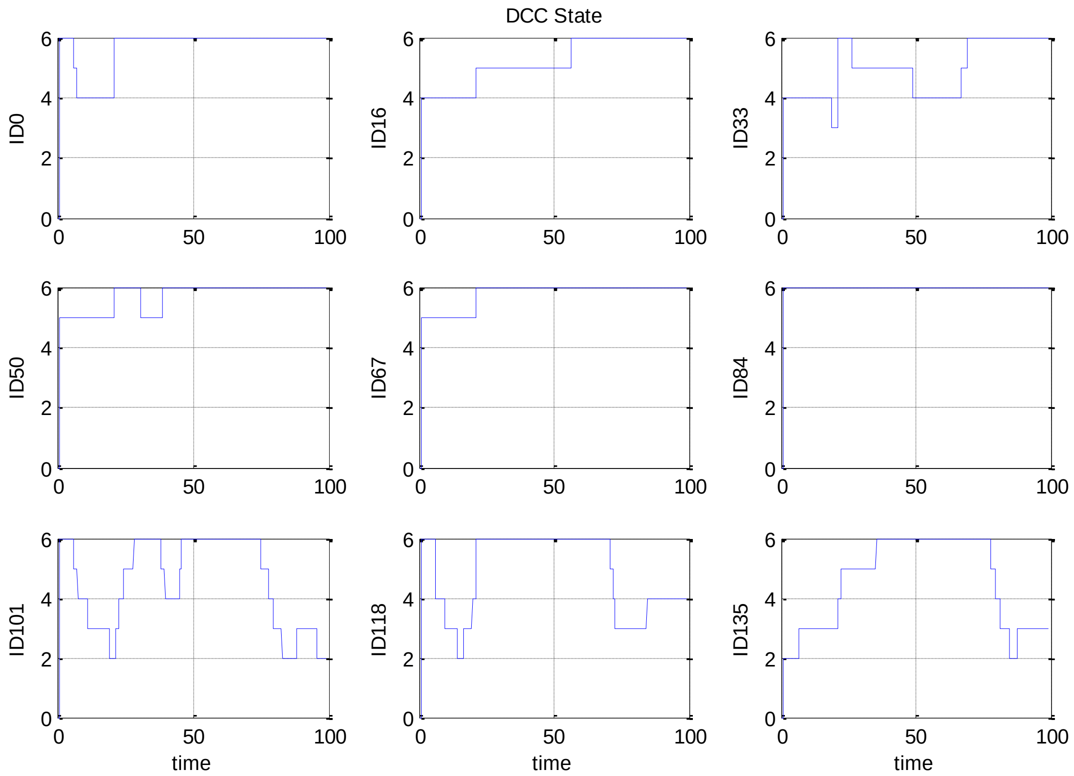


Figure 5-76: DCC state for 9 selected vehicles, DCC variant A, 512 vehicles

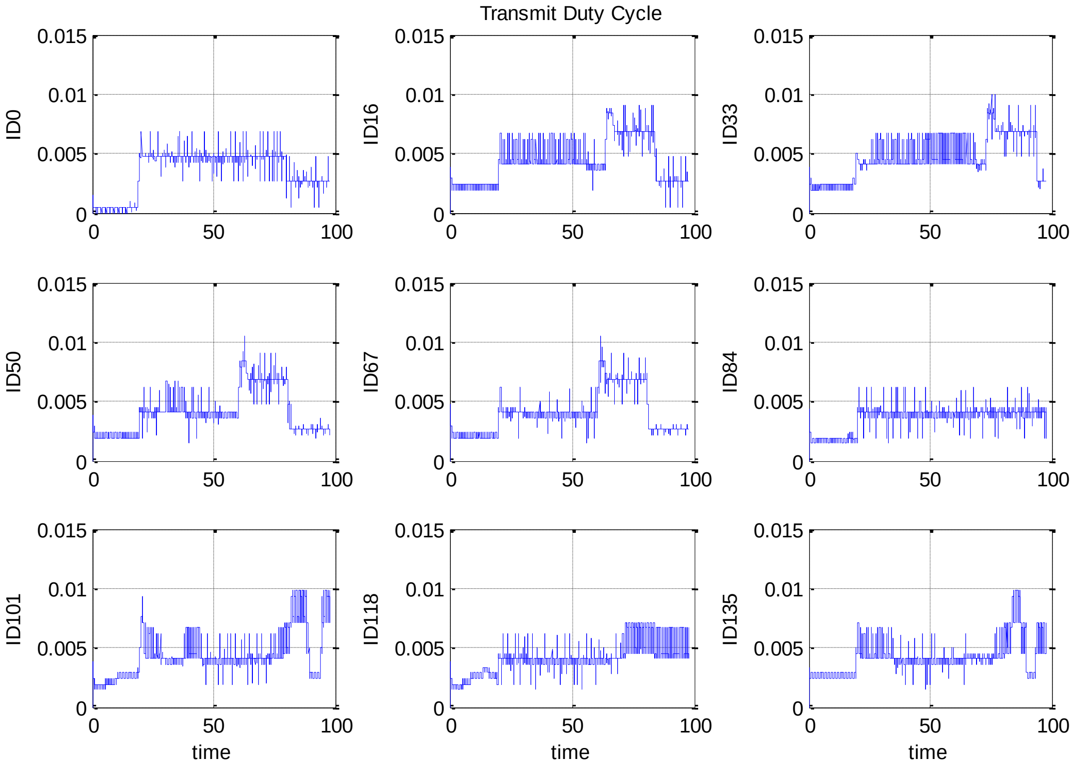


Figure 5-77: Duty cycle for 9 selected vehicles, DCC variant A, 512 vehicles

Figure 5-78 collects the mean and maximum duty cycles in both variants with and without the vehicle positions at the border of the highway section. A mean duty cycle of 0.4% and maximum duty cycle in between 0.6% and 1.1% are observed in the middle of the highway section. The maximum duty cycle is quite similar to the results for 256 vehicles. Nevertheless, the mean duty cycle is slightly smaller and less packets are transmitted at the border of the highway section.

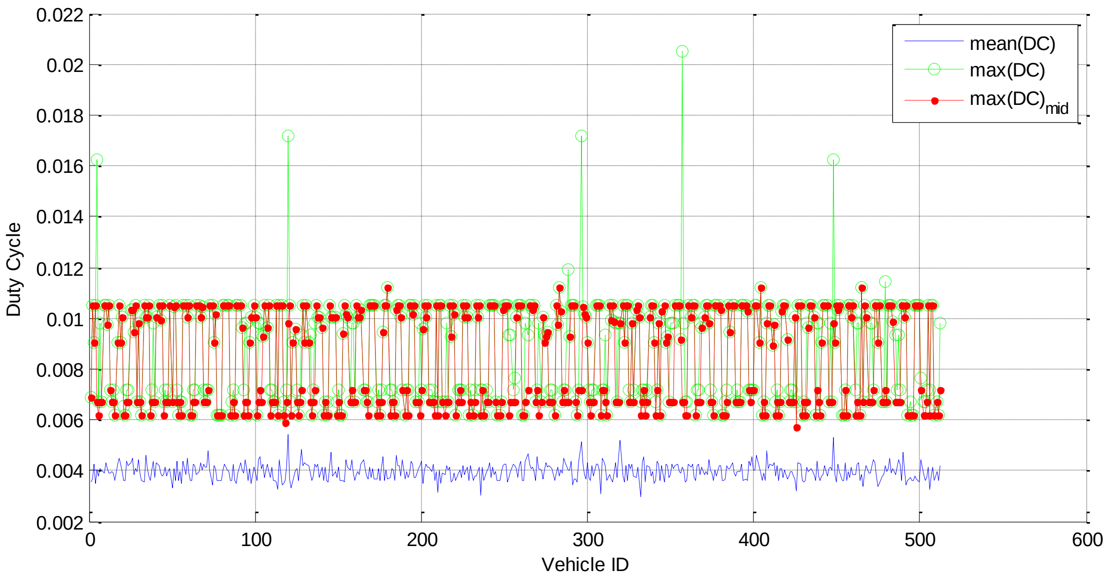


Figure 5-78: Mean and maximum duty cycle, DCC variant A, 512vehicles

5.2.4.2 Results for DCC variant B

Due to the higher channel load threshold for DCC states in variant B the DCC remains in *Active 4* after the crash. Nevertheless, the resulting channel load is almost identical to the results in Figure 5-74. This is at least true for a vehicle positioned in the middle of the highway section.

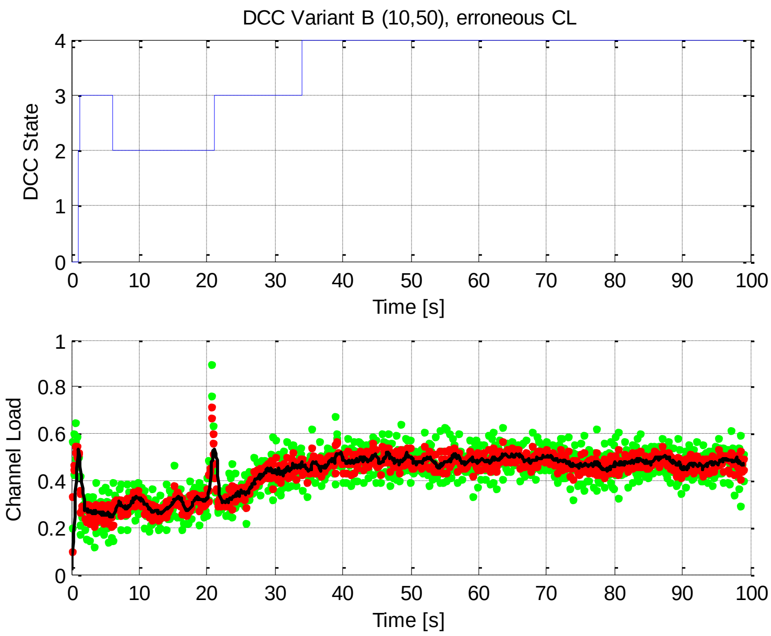


Figure 5-79: DCC state adaptation and measured channel load of vehicle ID0 for DCC variant B with NDL_TimeUp =1s. $NDL\_TimeDown$ =5s, 512 vehicles

The number of transmitted and received packets and the delays in DCC and MAC are summarised in Table 5-22.

DP1	DP1	CAM	DP3
CAM generation rule		566.4	
TxRequest	19.7	340.3	4137.9
TxPacket	19.7	337.0	42.5
RxPacket	2297	42179	3600
$\bar{d}_{DCC}$[s]	0.08	0.19	0.22
$std(d_{DCC})$ $[s]$	0.05	0.35	0.19
$\hat{d}_{DCC}$[s]	0.17	1.92	0.80
$\bar{d}_{MAC}$[ms]	0.45	0.84	1.77
$std(d_{MAC})$ [ms]	0.56	1.49	1.89
$\hat{d}_{MAC}$[ms]	2.44	13.37	7.29

Table 5-22: DCC variant B, 512 vehicles

For high vehicle densities DCC variant B seems to be more restrictive than variant A, since the average number of CAMs as well as the number of DP3 packets is lower. While the reduction is small for CAM packets, the number of DP3 packets is more than halved. As shown in the lowest plot of Figure 5-80 the number of transmitted DP3 packets per vehicles significantly varies ranging from 2 to 190.

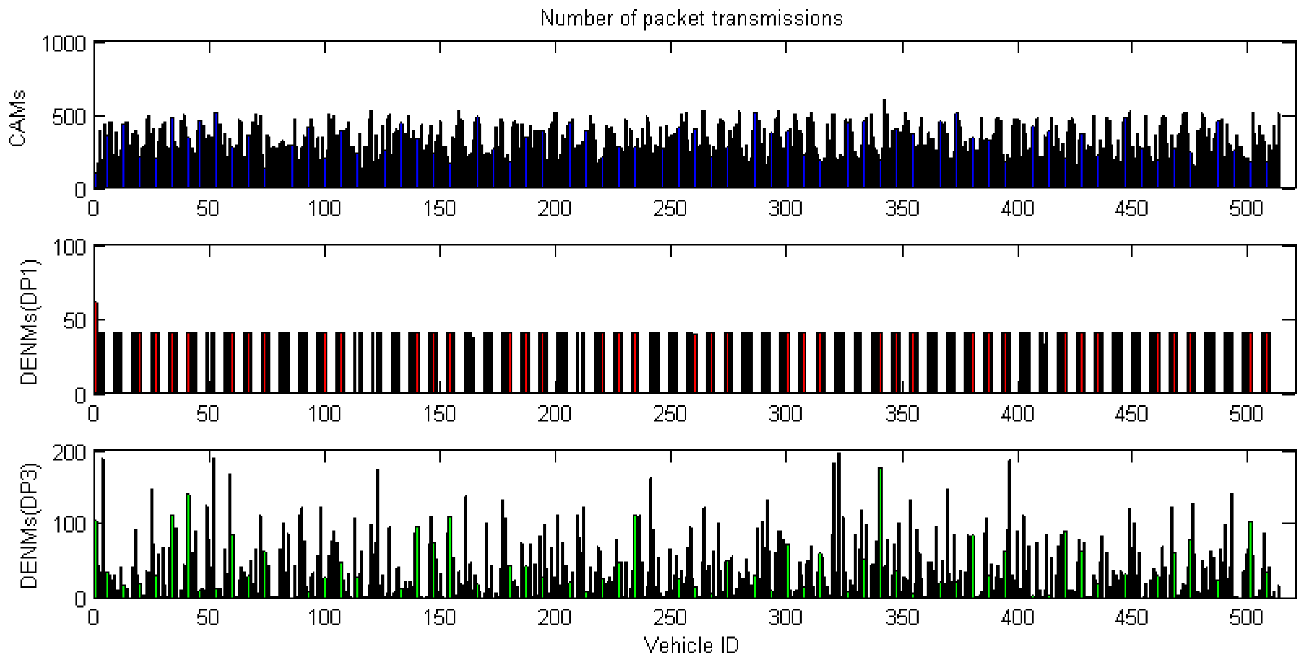


Figure 5-80: Number of transmitted packets as a function of priority, DCC variant B, 512 vehicles

DCC state and duty cycle of the nine selected vehicles are shown in Figure 5-81 and Figure 5-82, respectively.

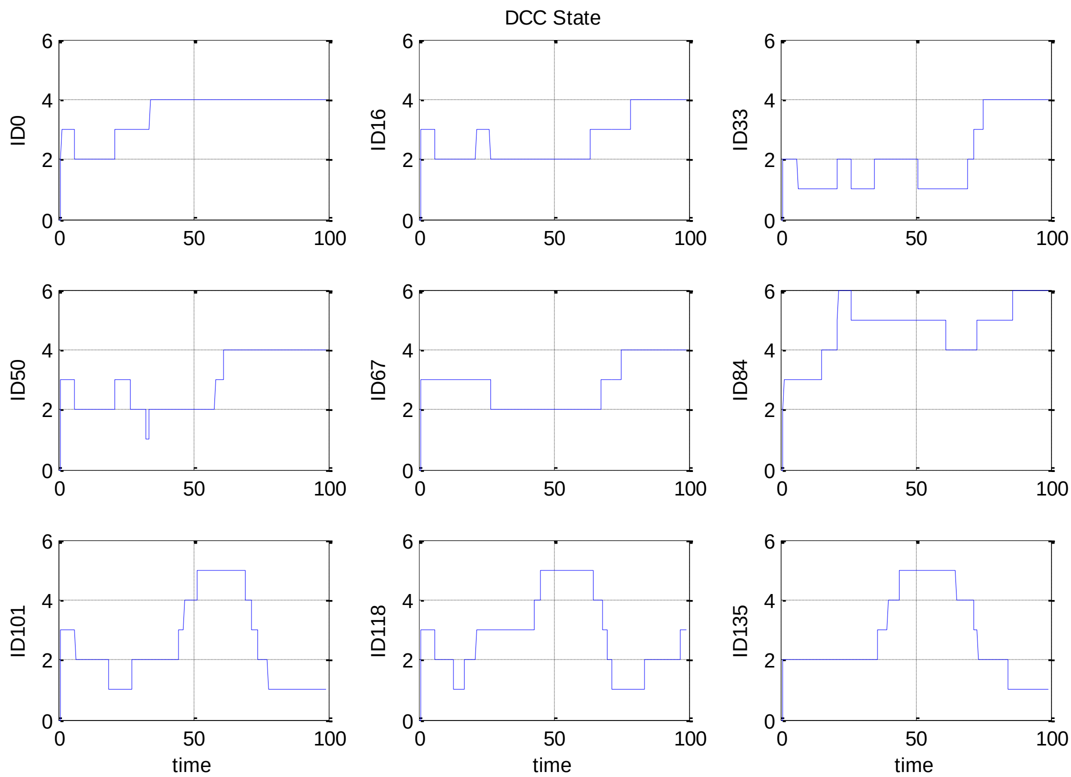


Figure 5-81: DCC state for 9 selected vehicles, DCC variant B, 512 vehicles

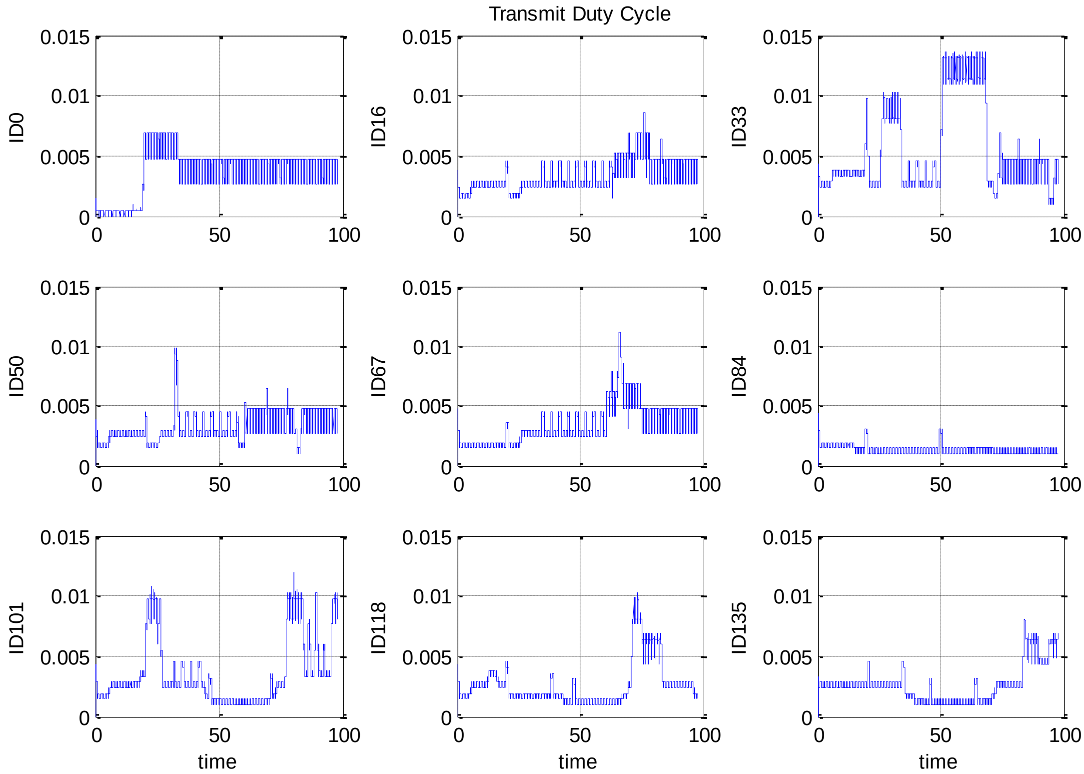


Figure 5-82: Duty cycle for 9 selected vehicles, DCC variant B, 512 vehicles

Although the total number of transmitted packets is lower for DCC variant B than for variant A, the maximum duty cycle can be even higher. It seems that more packets are transmitted at the border of the highway section. This can be also observed comparing the mean and maximum duty cycle for all simulated vehicles to the results for DCC variant A in Figure 5-78.

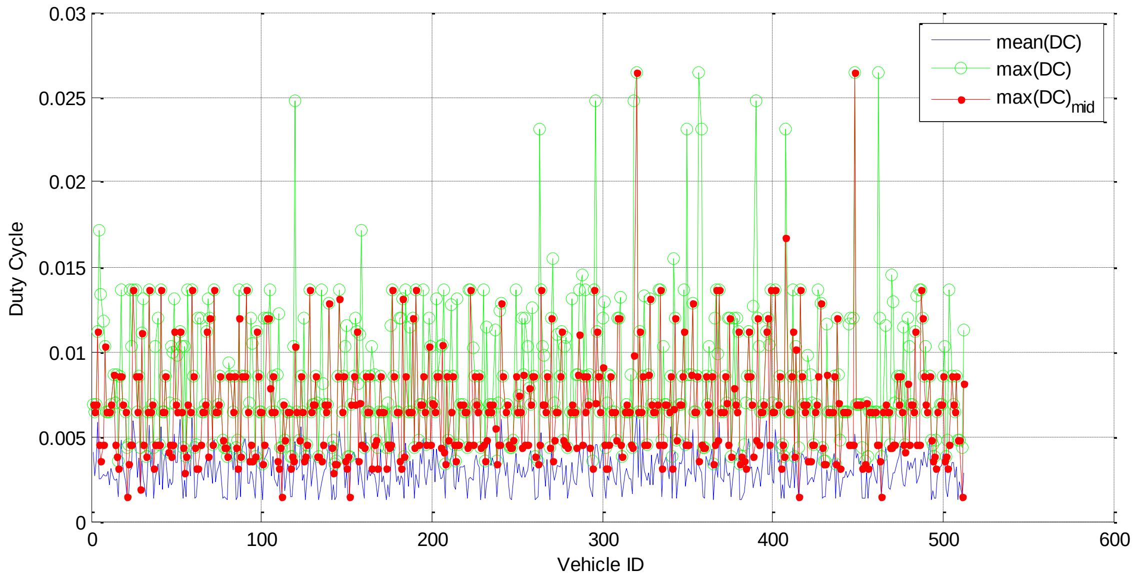


Figure 5-83: Mean and maximum duty cycle, DCC variant B, 512 vehicles

In DCC variant A, the maximum duty cycle measured in the middle of the highway section has been varying between 0.6% and 1.1%. The range is much larger for DCC variant B. Hence, a common packet distance for all DP1, CAM, and DP3 packets does not necessarily results in a similar duty cycle. Low speed vehicles or even those captured within the traffic jam are sending more DP3 packets than those travelling in the opposite direction with relatively high speed. Due to the larger duration of DP3 packets the resulting duty cycle can be significantly higher for slow vehicles.

5.2.4.3 Results for modified DCC variant A

In the original DCC variant A the DCC state for vehicle ID0 has been in *Restrictive* even in the pre-crash phase as shown in Figure 5-74. Due to the higher channel load thresholds, the corresponding DCC state in the modified DCC variant is now *Active 3*. Nevertheless, there seems to be no significant difference with regards to the measured channel load except that even the filtered channel load slightly oscillates.

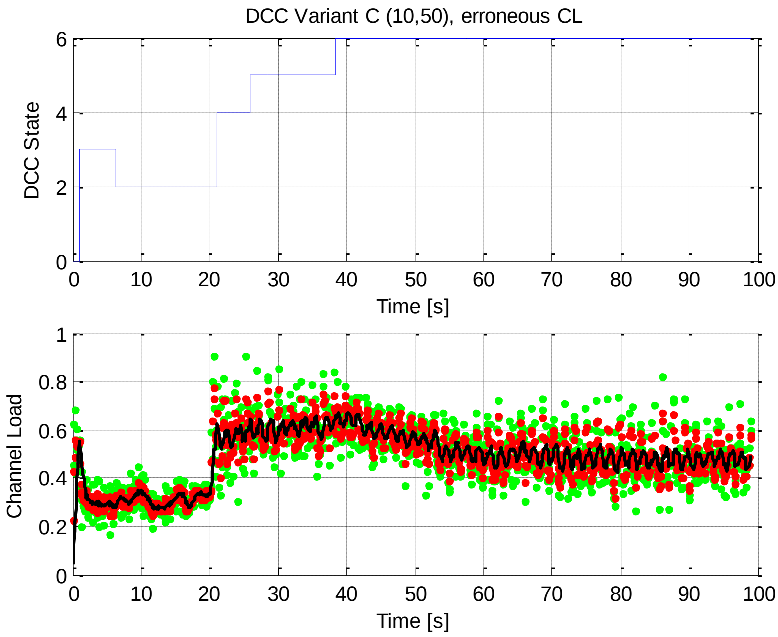


Figure 5-84: DCC state adaptation and measured channel load of vehicle ID0 for modified DCC variant A with NDL_TimeUp =1s. $NDL\_TimeDown$ =5s, 512 vehicles

Looking at the number of transmitted packets, there are 7.5% less CAMs and 20% less DP3 packet transmissions compared to the original DCC variant A. The smaller number of transmissions can be explained by the higher minimum packet distances for channel loads above 42% for the modified DCC variant A (see Figure 3-5).

DP1	DP1	CAM	DP3
CAM generation rule		566.4	
TxRequest	19.7	327.9	5172.1
TxPacket	19.7	327.9	67.1
RxPacket	2133	39768	5648
$\bar{d}_{DCC}$[s]	0	0	0.14
$std(d_{DCC})$ $[s]$	0	0	0.19
$\hat{d}_{DCC}$[s]	0	0	1.02
$\bar{d}_{MAC}[\mathrm{ms}]$	0.69	1.36	4.10
$std(d_{MAC})$ $[\mathrm{ms}]$	0.82	2.47	5.55
$\hat{d}_{MAC}[\mathrm{ms}]$	3.68	23.02	33.21

Table 5-23: Modified DCC variant A, 512 vehicles

The DCC delay for DP3 packets is almost identical, but all MAC delays are larger in the modified version although the channel load should be smaller. The effect might be caused by the channel load oscillations observed in Figure 5-84, resulting in larger waiting times for channel access during high channel load phases. Nevertheless, MAC delays are small compared to DCC delays so that the higher MAC delays are assumed to be no problem.

The number of transmitted packets is shown in Figure 5-85. Each vehicle transmits at least 49 DP3 packets during the 80 s of post-crash phase simulation, compared to 72 packets in the original DCC variant A. This number is now reduced as a consequence of the increased packet distances for high channel loads.

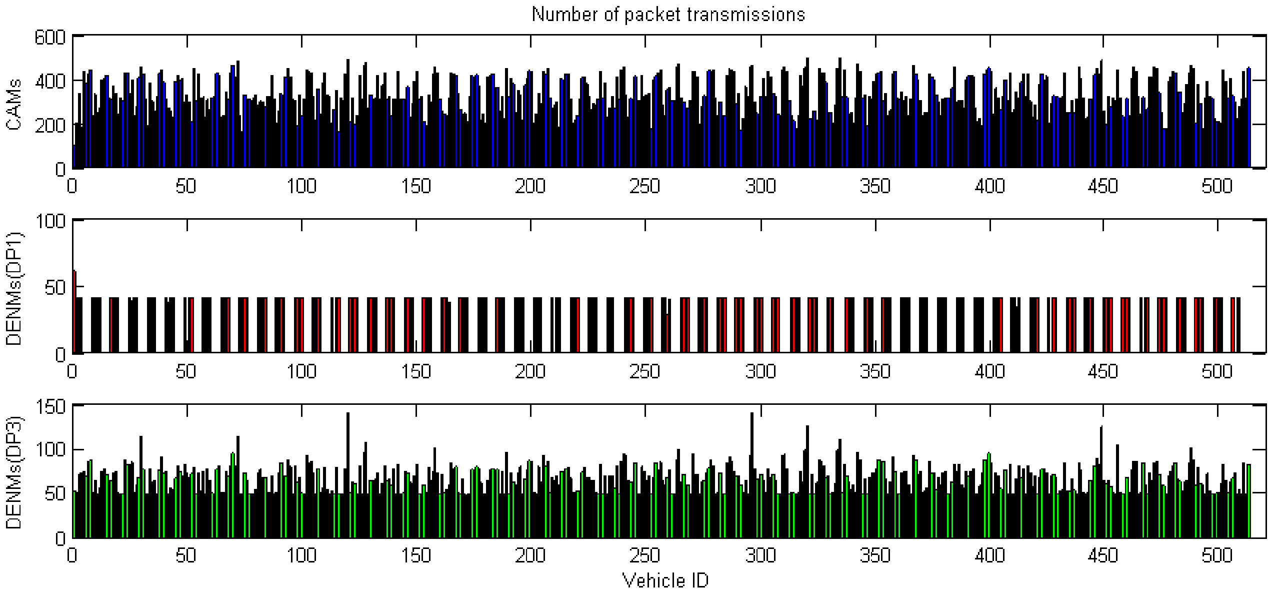


Figure 5-85: Number of transmitted packets as a function of priority, modified DCC variant A, 512 vehicles

Depending of the position of the vehicle, DCC states typically range in between *Active 2* and *Restrictive*. The DCC states are often a bit higher than in DCC variant B, which uses the same CL thresholds. This is caused by the higher number of DP3 transmissions (+58%).

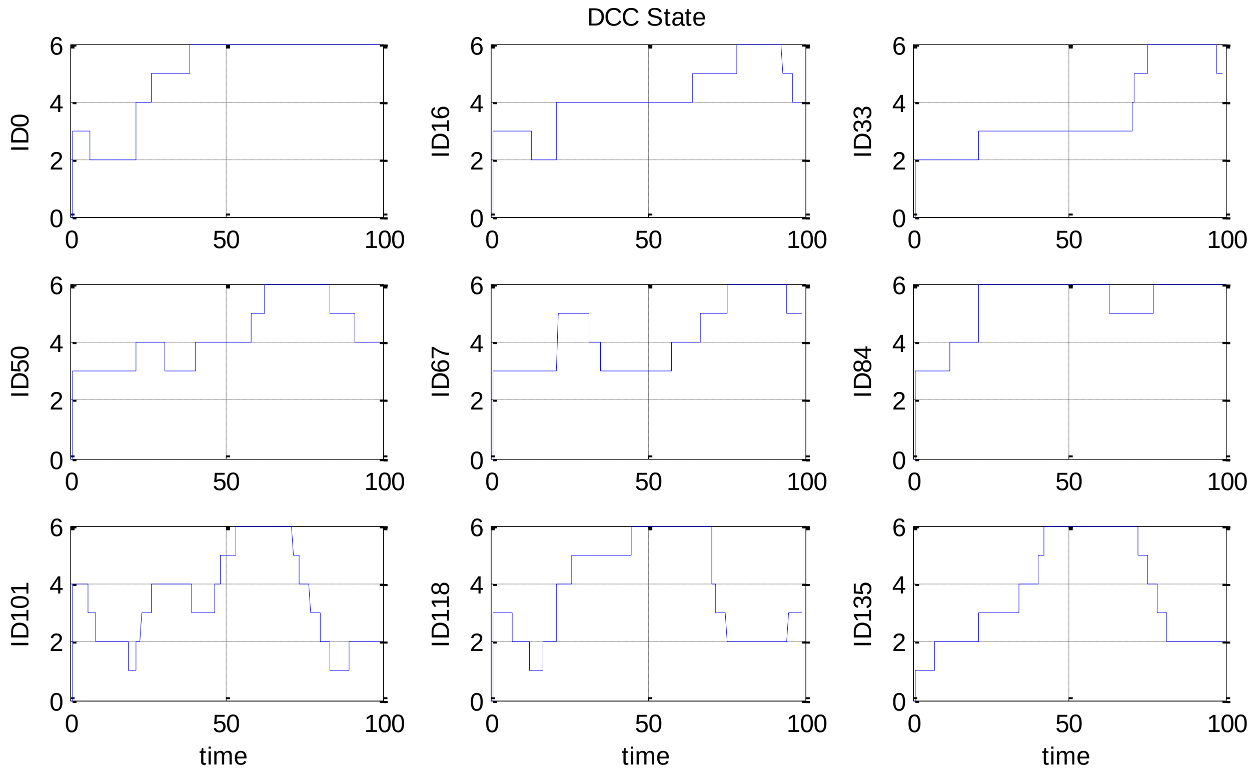


Figure 5-86: DCC state for 9 selected vehicles, modified DCC variant A, 512 vehicles

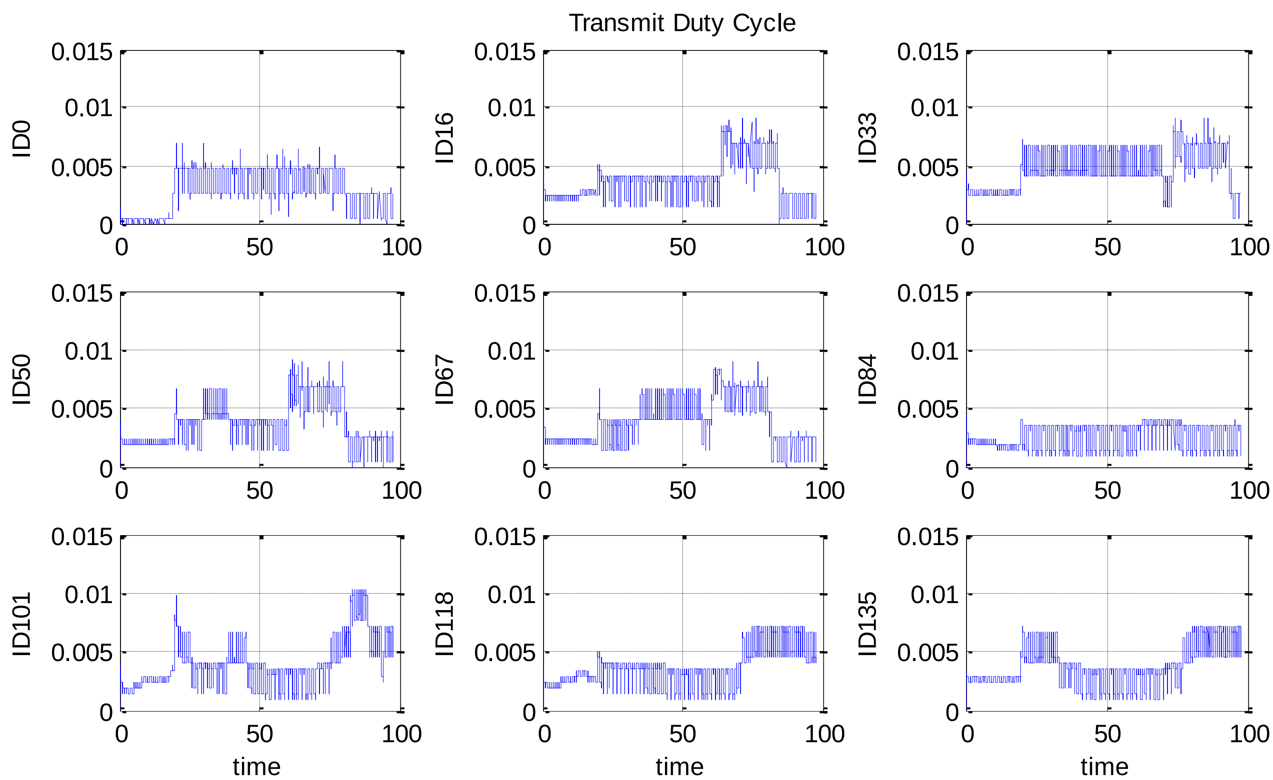


Figure 5-87: Duty cycle for 9 selected vehicles, modified DCC variant A, 512 vehicles

Mean and maximum duty cycle are shown in Figure 5-88. Only three vehicles show up with a peak duty cycle of more than 2.5% at the border of the highway section, while all the others are close to 1% or below.

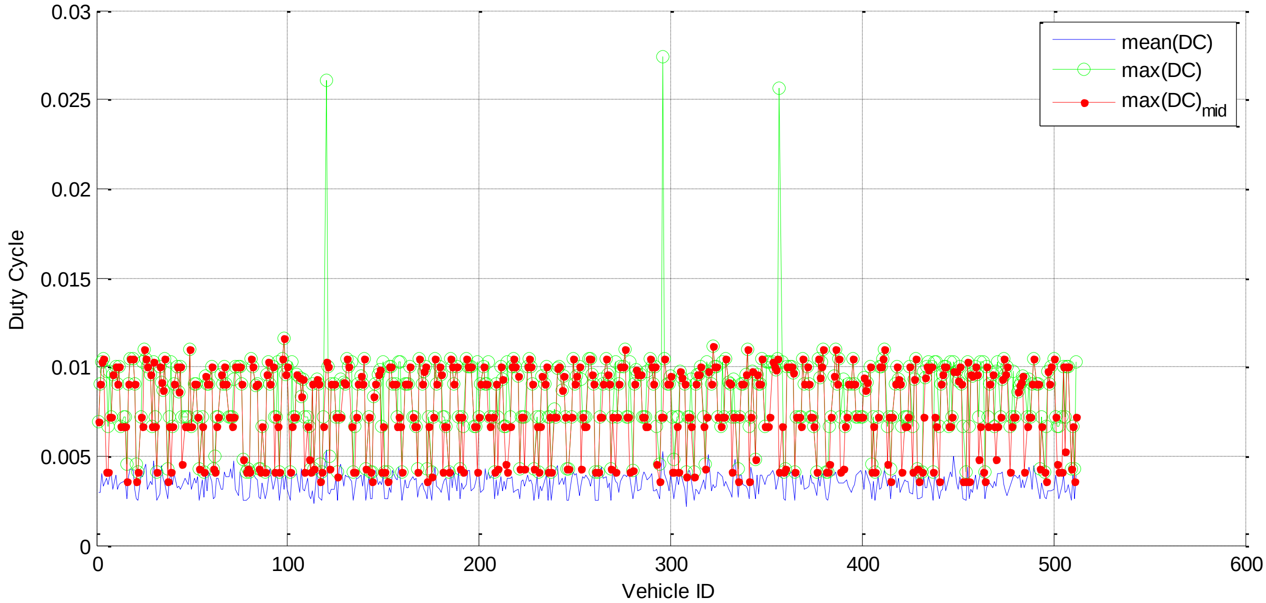


Figure 5-88: Mean and maximum duty cycle, modified DCC variant A, 512 vehicles

5.2.4.4 Results for DCC variant C

Introducing duty cycle limitation to the DP3 transmission queue slightly reduces the channel load for vehicle ID0 in the post-crash phase and damps the channel load oscillations.

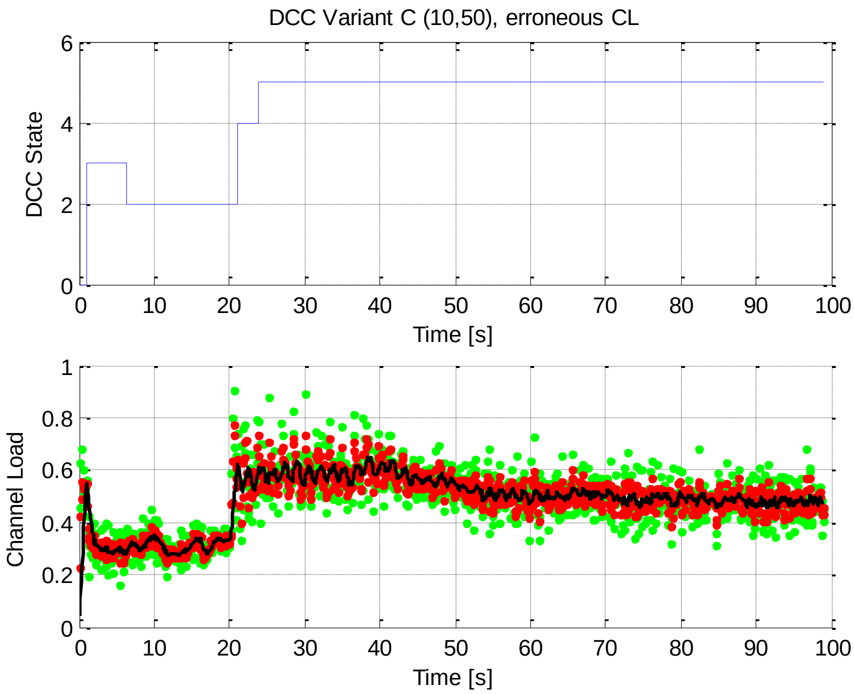


Figure 5-89: DCC state adaptation and measured channel load of vehicle ID0 for DCC variant C with NDL_TimeUp =1s. $NDL\_TimeDown$ =5s, 512 vehicles

The total number of DP3 transmissions has been lowered by only 4% compared to the modified DCC variant A. This reduction is small, because the duty cycle of all vehicles is already quite low as shown in Figure 5-88. In general, it might be reasonable to reduce DP3 packet transmissions by a significantly higher degree as the cumulative number of DP3 packets does not needs to be larger than in a scenario with a small number of vehicles in order to forward emergency information to approaching vehicles. Using lower duty cycle limits for high DCC states is expected to reduce the number of DP3 packets. This will be investigated in section 6.

DP1	DP1	CAM	DP3
CAM generation rule		566.4	
TxRequest	19.7	330.4	5104.9
TxPacket	19.7	330.4	64.3
RxPacket	2171	40563	5499
$\bar{d}_{DCC}[\mathrm{s}]$	0	0	0.14
$std(d_{DCC})\ [s]$	0	0	0.18
$\hat{d}_{DCC}[\mathrm{s}]$	0	0	1.00
$\bar{d}_{MAC}[\mathrm{ms}]$	0.61	1.23	3.08
$std(d_{MAC})\ [\mathrm{ms}]$	0.67	2.15	5.21
$\hat{d}_{MAC}[\mathrm{ms}]$	3.01	20.55	31.20

Table 5-24: DCC variant C, 512 vehicles

The number of transmitted packets shows almost no difference with regards to the CAM and DP1 transmissions compared to the modified DCC variant A. Nevertheless, larger variations in the number of DP3 packet transmissions are observed.

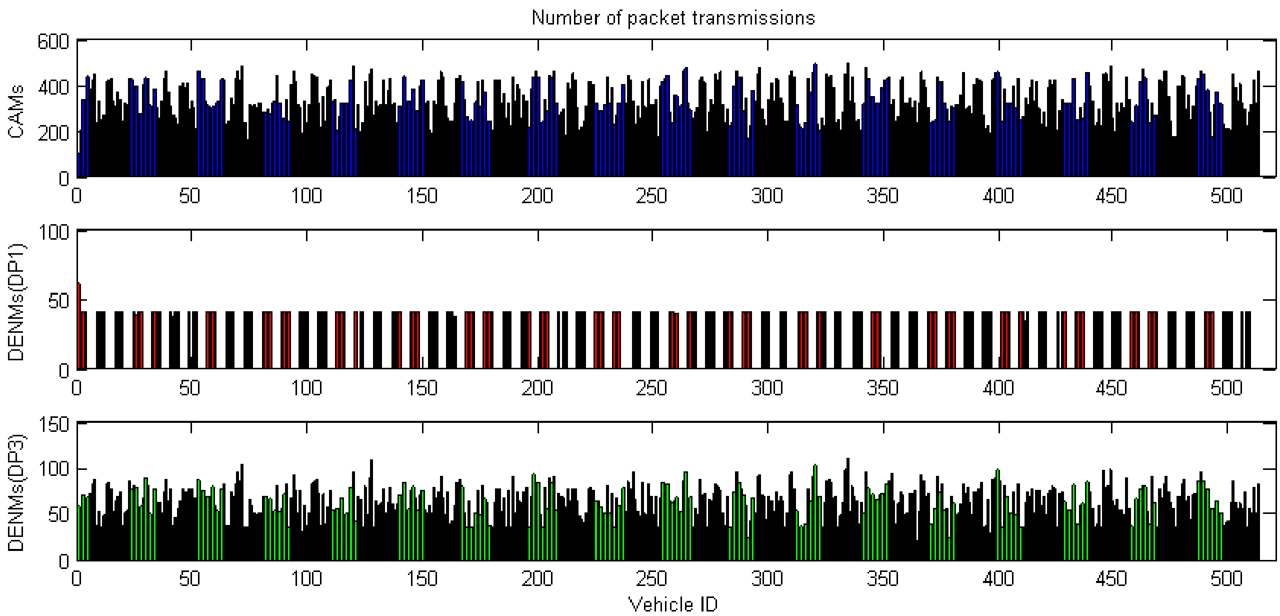


Figure 5-90: Number of transmitted packets as a function of priority, DCC variant C, 512 vehicles

DCC state as well as duty cycle of the 9 selected vehicles are again quite similar to the ones observed for the modified DCC version A.

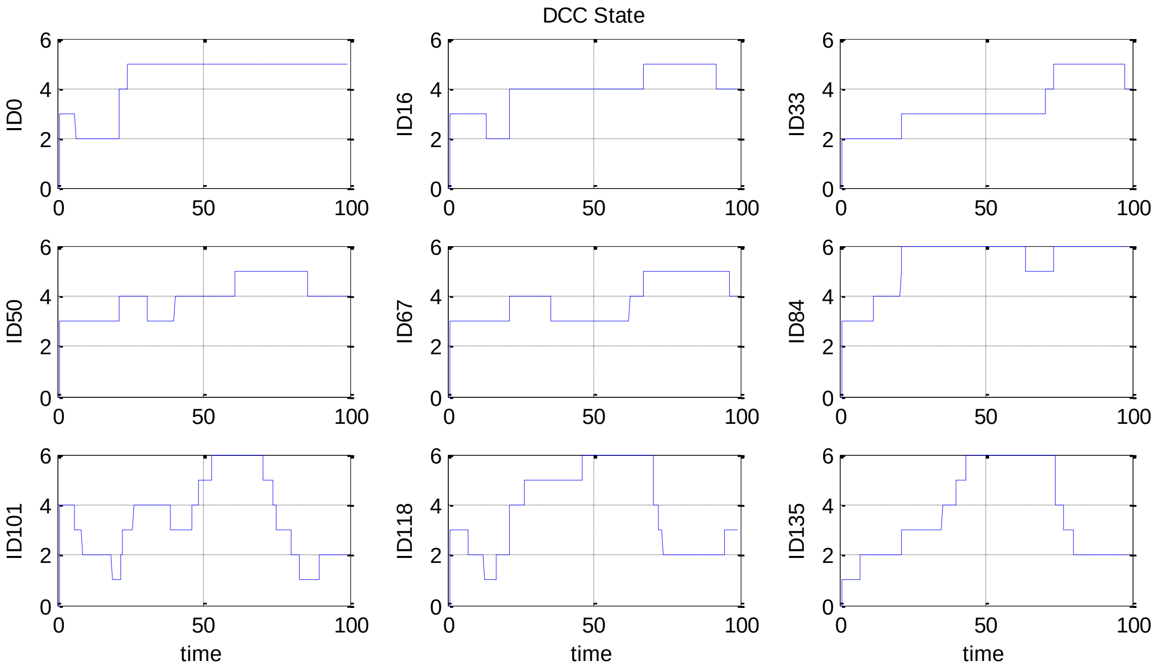


Figure 5-91: DCC state for 9 selected vehicles, DCC variant C, 512 vehicles

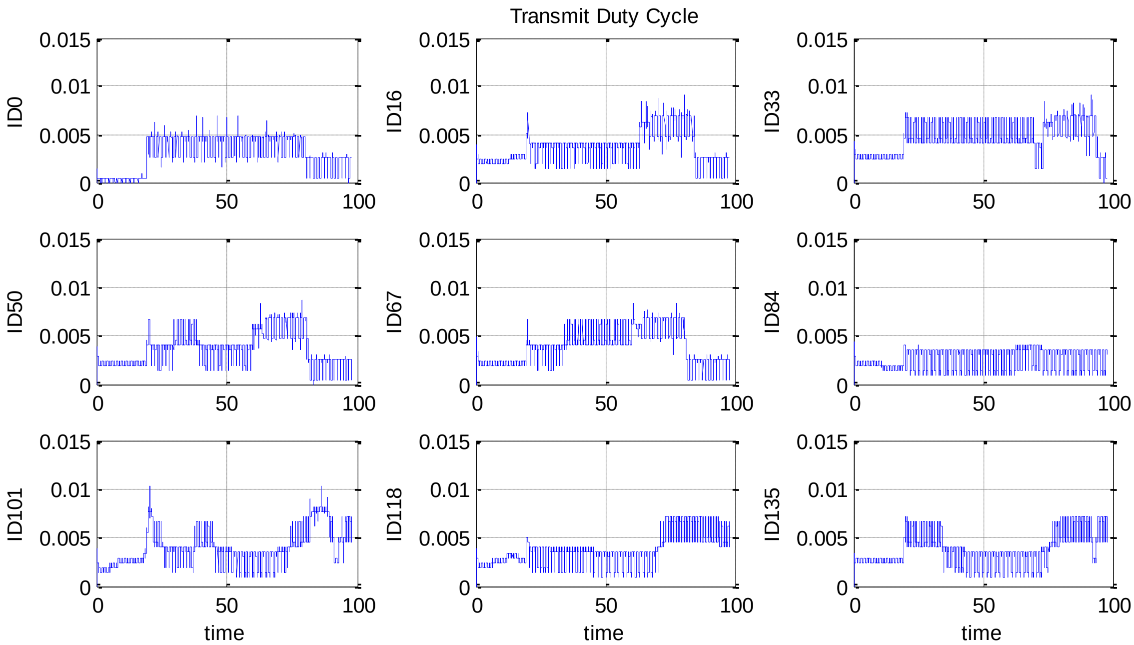


Figure 5-92: Duty cycle for 9 selected vehicles, DCC variant C, 512 vehicles

As shown in Figure 5-93 the duty cycle limitation removes the large duty cycle peaks at the border of the highway. Additionally, some of the peaks close to 1% are slightly reduced when compared to the modified version of DCC variant A.

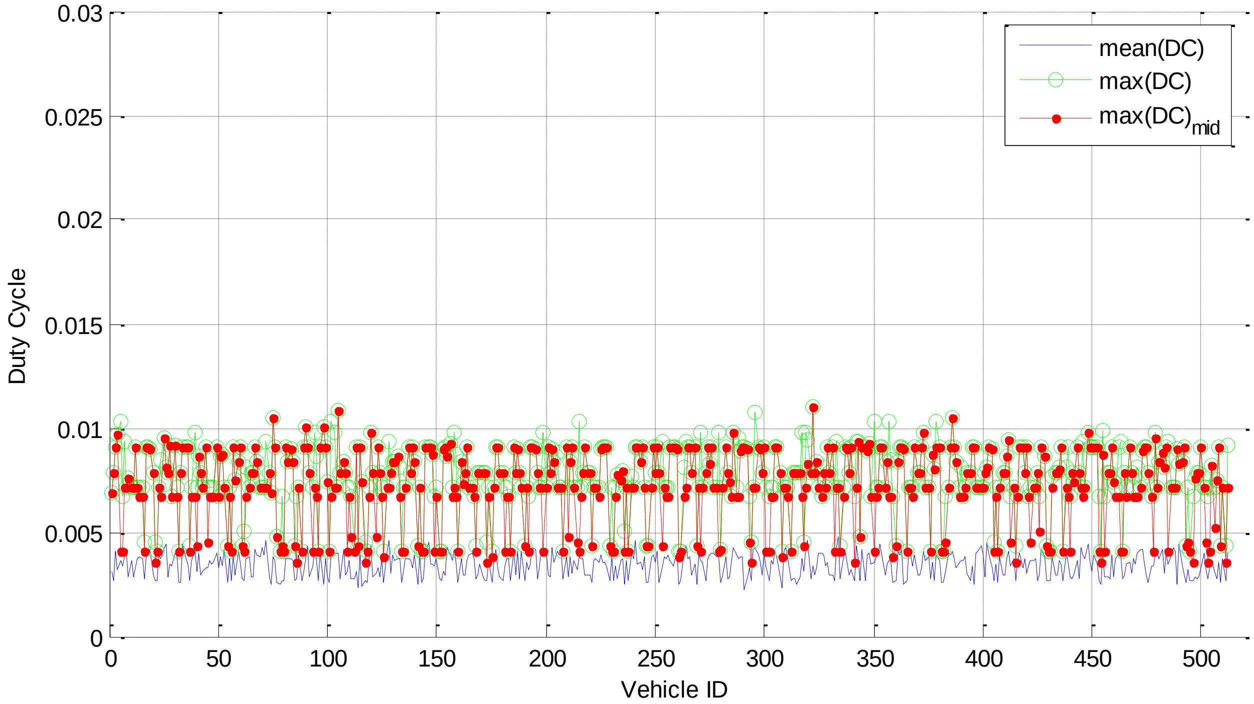


Figure 5-93: Mean and maximum duty cycle, DCC variant C, 512 vehicles

5.2.4.5 Position Error

As for the low vehicle numbers the position error based on the CAM generation rule without DCC limitations is close to 4 m. Taking DCC variant A into account, the position error based on the transmitted CAMs is shown on the right side of Figure 5-94. Almost all position errors are below 10 m although the probability of a higher error is slightly larger than in the previous simulation with 256 vehicles (see Figure 5-65).

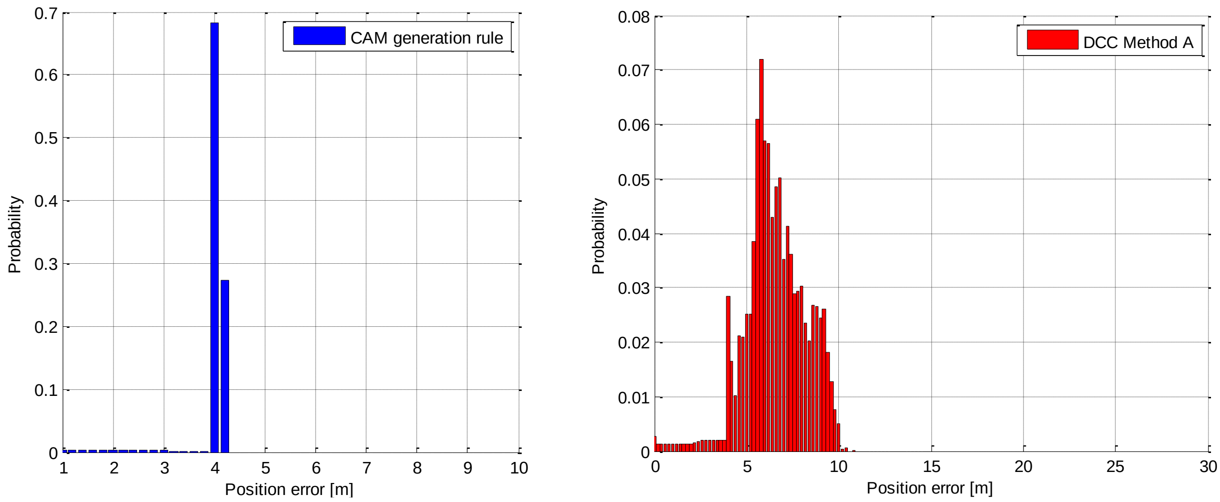


Figure 5-94: Probability of position error for using CAM generation rule and no DCC limitations (left) and DCC variant A (right) based on transmitted CAM packets

The same analysis is done for DCC variant B and the results are shown for a CAM queue length of 5 packets on the left side and a queue length of 1 packet on the right side of Figure 5-95. The probability of a position error close to 4 m is significantly higher than using DCC variant A, as smaller CAM intervals are allowed in DCC variant B compared to variant A during the pre-crash phase. Nevertheless, the position errors after the crash are again much larger.

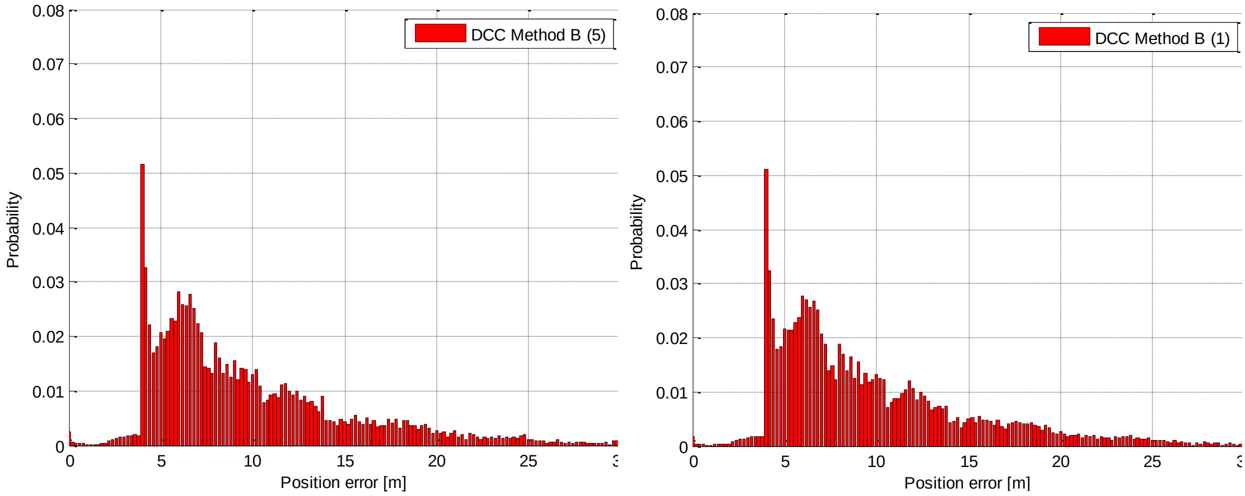


Figure 5-95: Probability of position error for DCC variant B with a CAM queue length of 5 (left) and 1 packet (right) based on transmitted CAM packets

Significantly lower position errors can be obtained with the modified DCC variant A and DCC variant C on the left and right side of Figure 5-96, respectively. Errors are typically below 13 m, so that the results are slightly worse than in the original DCC variant A due to larger minimum CAM intervals at higher DCC states. If necessary the position error are expected to be smaller using higher packet rates for CAMs or decreasing the DC limits for DCC variant C. This will be investigated in section 6.

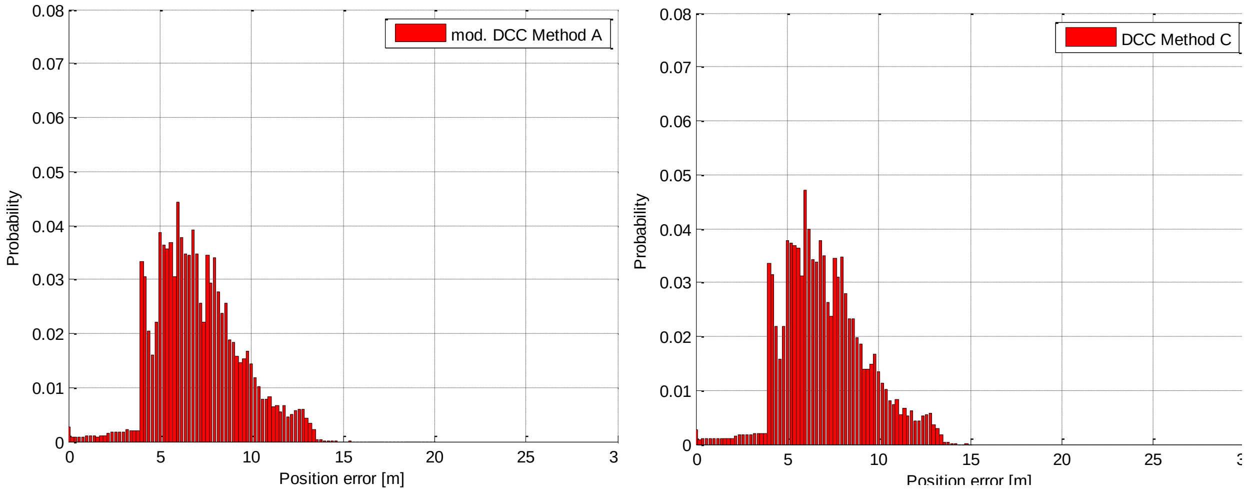


Figure 5-96: Probability of position error for modified DCC variant A (left) and DCC variant C (right) based on transmitted CAM packets

Table 5-25 provides the statistical data for the different DCC variants and position errors based on CAM transmit times.

Position Error	Variant A	Variant B(5)	Variant B(1)	mod. Variant A	DCC variant C
mean	6.66	9.82	9.83	7.20	7.13
standard deviation	1.67	5.52	5.54	2.32	2.28
max	10.99	35.7	34.94	15.60	14.88

Table 5-25: Position errors for the different DCC variants in a highway scenario with 512 vehicles

Finally the position error is calculated based on the received CAM packets. If packet losses are included, the position error increases, so that large position errors above 30 m are observed for all DCC variants. Nevertheless, the majority of the errors are significantly smaller using the original or modified DCC variant A and DCC variant C, while DCC variant B has a much higher probability for position errors above 10 m for both DCC queue length settings. Comparing the CDFs on the right side of Figure 5-99 shows that 90% of the position errors are below 15 m in DCC variant A and C, while up to 21 m are obtained using DCC variant B.

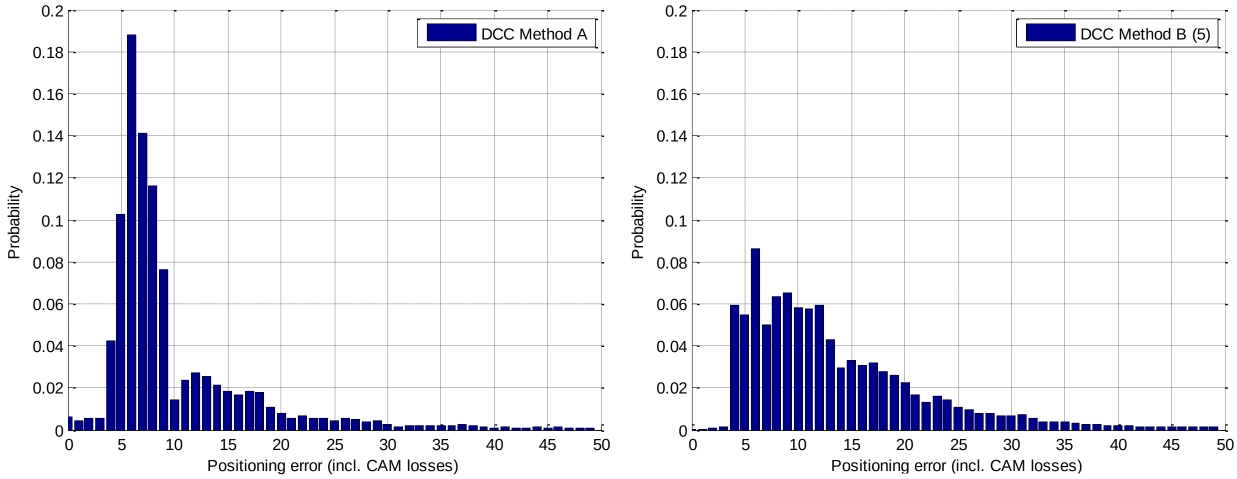


Figure 5-97: Probability of position error for DCC variant A (left) and DCC variant B with a CAM queue length of 5 (right) based on received CAM packets, 512 vehicles

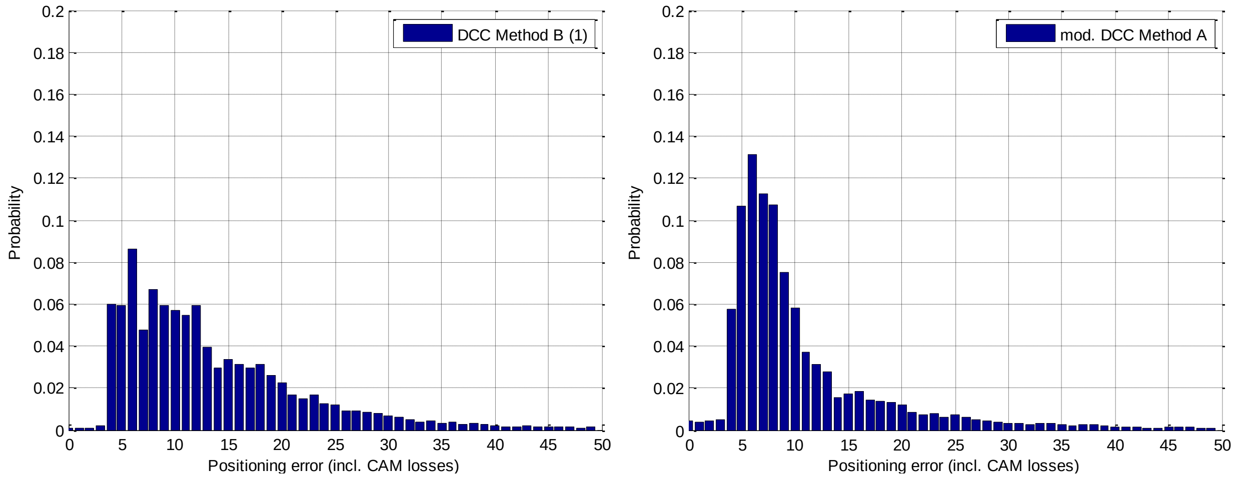


Figure 5-98: Probability of position error for DCC variant B with a CAM queue length of 1 (left) and modified DCC variant A (right) based on received CAM packets, 512 vehicles

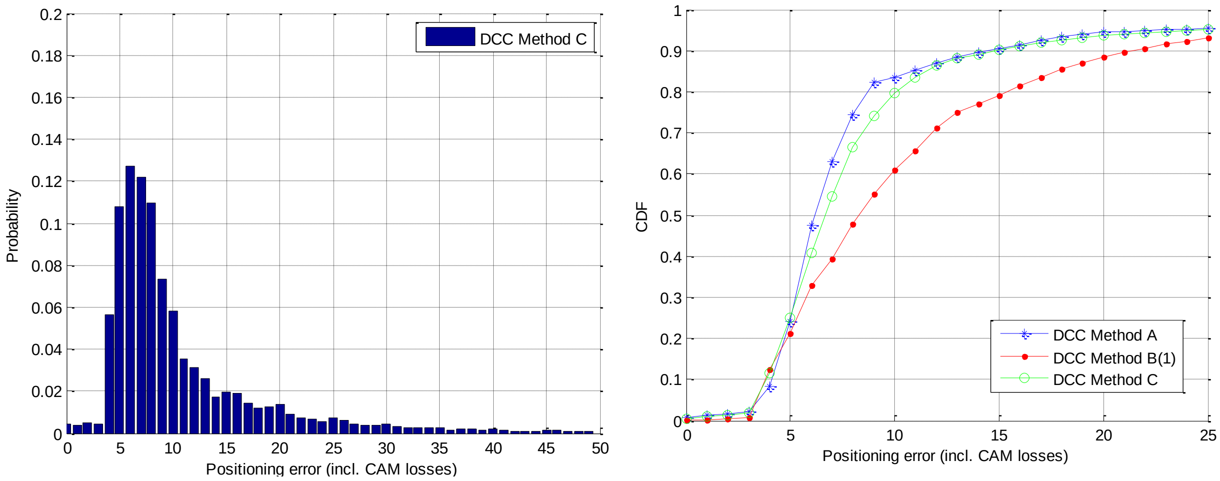


Figure 5-99: Probability of position error for DCC variant C and CDF, 512 vehicles

5.2.4.6 Packet collision rates

Doubling the number of vehicles in the simulations increases the mean packet collision rate from 19% to 27% during the pre-crash phase. The difference between the DCC variants is quite small, so that their restrictions on CAM packet rates seem to be quite similar for higher channel loads.

Packet Collision Rate	variant A	variant B (5) / (1)	mod. variant A / variant C
mean	0.271	0.277	0.269
median	0.243	0.253	0.242
standard deviation	0.103	0.099	0.103

Table 5-26: Packet collision rates in the pre-crash phase, 512 vehicles

As expected higher collision rates are observed after the crash. The DCC variant B performs best due to the significantly lower number of DP3 packet transmissions. The collision rates of DCC variant C are slightly smaller than the results of DCC variant A and its modified version, but the differences are small.

Packet Collision Rate	variant A	variant B (5)	variant B (1)	mod. variant A	variant C
mean	0.397	0.317	0.317	0.388	0.375
median	0.357	0.285	0.284	0.348	0.334
standard deviation	0.115	0.103	0.103	0.12	0.119

Table 5-27: Packet collision rates in the post-crash phase, 512 vehicles

One again, the three DCC variants do not differ with regards to their packet collision rate as a function of the channel load also for high vehicles densities. Note that the same result has been obtained for 128 and 256 vehicles (see Figure 5-40 and Figure 5-71).

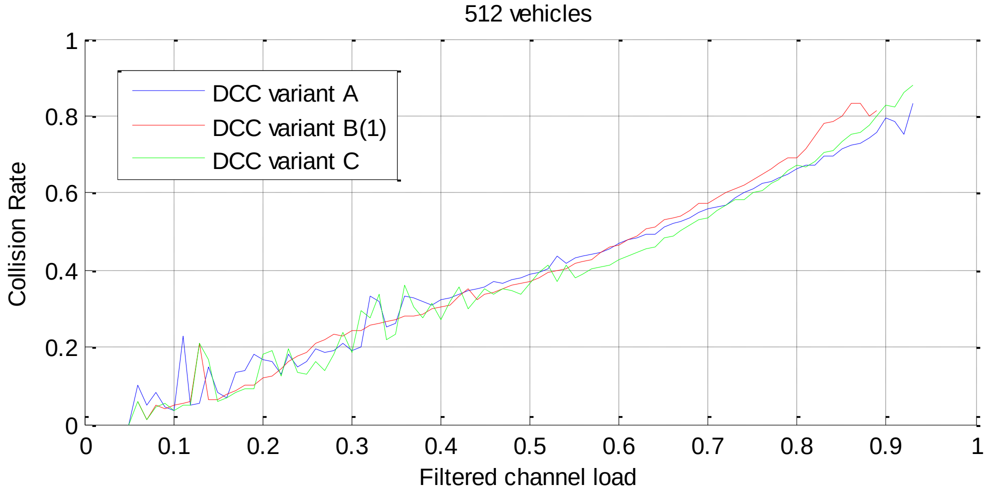


Figure 5-100: Collision rate as a function of filtered channel load for 512 vehicles

In general, a collision rate up to 40% as observed for DCC variant A and C is assumed to be unreasonably high.

The figure below compares the probability of the measured channel load for the three DCC variants. The curves are almost identical in the pre-crash phase , while a lower channel load is obtained for DCC variant B in the post-crash phase.

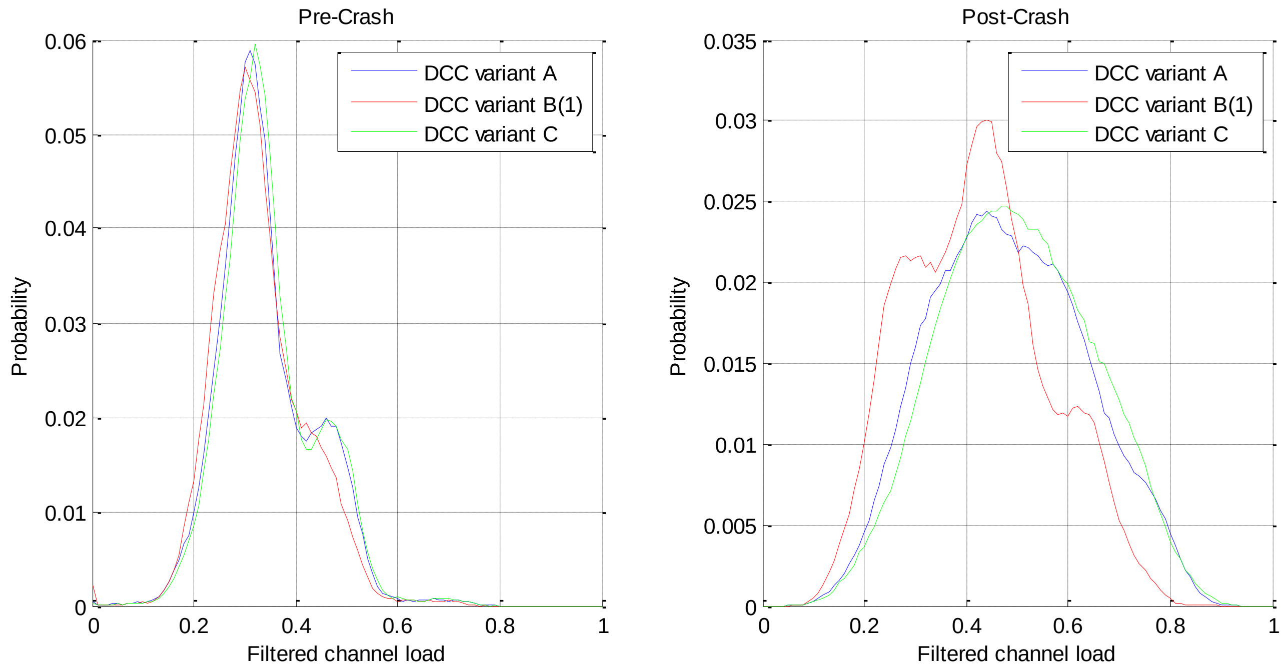


Figure 5-101: Probability function of the filtered channel load during pre-crash and post-crash phase, 512 vehicles

Mean value and standard deviation of the packet collision rate are listed for the pre-crash and post-crash phase in Table 5-28. The mean value for DCC variant C during the post-crash phase is 8% higher compared to DCC variant B.

	Filtered channel load	variant A	variant B (1)	variant C
Pre-crash	mean	34.7 %	33.3 %	35.3 %
	standard deviation	9.3 %	8.9 %	9.2 %
Post-crash	mean	48.8 %	42.6 %	50.4 %
	standard deviation	15.1 %	14.0 %	14.9 %

Table 5-28: Packet collision rates in the post-crash phase, 512 vehicles

Section 6 will look for modified parameters settings to reduce the number of DP3 packets, so that the channel load will be smaller resulting in a lower packet collision rate.

5.3 Conclusions

All DCC variants succeed in limiting traffic on the air interface in case of higher vehicles densities. The resulting channel loads as well as packet collision rates are quite comparable. Nevertheless, each variant has its specific characteristics:

(Modified) DCC variant A:

- No DCC delay for CAM packets as the facilities layer can generate CAMs at exactly the correct rate
- No DCC delay for DP1 packets supposed that the repetition or update interval is larger than the minimum packet distance for DP1 packets in the DCC. This is true for most triggering conditions in Day One except “Dangerous situation” and “Collision Risk”
- Relatively small position errors as CAM are transmitted without delay in the DCC. The position errors of the modified DCC variant A are slightly higher for higher vehicle densities due to the smaller CAM packet rates defined for channel loads above 42%. If necessary, the parameterisation of the modified variant can be easily modified to allow shorter CAM packet distances to improve position accuracy.
- All vehicles forward a comparable number of DENMs packets (DP3). This results in a higher duty cycle for the vehicles travelling in the upstream direction because they additionally transmit the “Traffic jam ahead “ DENMs (DP1).

DCC variant B:

- DCC delay for DP1 packets is distributed in [0, T_{OFF}], where T_{OFF} is the minimum packet distance of the current DCC state
- No DCC delay for CAM packets as long as there are neither DP1 nor DP3 packets
- Outside DP1 transmission phase, the delay of CAM packets is in the order of [0, T_{OFF}] if DP3 packets are transmitted.
- During DP1 transmission phase, only a reduced number of CAMs are transmitted. Two strategies have been investigated: the remaining ones are either stored in the DCC queue or replaced by the new one (DCC queue length is 1). The performance of both strategies has been almost identical in the simulated scenario, as “Traffic jam ahead“ (DP1) packets are transmitted at vehicle speed below 30 km/h, where the position stored in the CAM does not change significantly from one CAM to the next.
- Relatively high position errors are resulting from the CAM delay in the DCC compared to DCC variant A
- Although a common packet distance for DP1, CAM, and DP3 packets suggests a similar maximum duty cycle, this is not confirmed in the simulation. As the duration CAM packets are much shorter than those of DP1 and DP3 packets, vehicles travelling in the downstream direction with high speed are transmitting with a lower duty cycle due to the higher number of CAM packets. The range of the maximum duty cycle for all vehicles is even larger than in DCC variant A.

DCC variant C:

- Same advantages than DCC variant A, as just duty cycle limits for DP3 packet transmissions are added
- No DCC delay for CAM packets as the facilities layer can generate CAMs at exactly the correct rate
- No DCC delay for DP1 packets supposed that the repetition or update interval is larger than the minimum packet distance for DP1 packets in the DCC. This is true for most triggering conditions in day 1 except “Dangerous situation” and “Collision Risk”
- Position error is almost identical to the position error of the modified DCC variant A and hence significantly lower than for DCC variant B. Improvements can be simply done lowering the CAM packet distances at high channel loads.
- A duty cycle limit allows to transmit DP3 packet only if the minimum distance to the previous DP3 packet is met and the overall duty cycle is below a certain threshold. Hence, only a few or even no DP3 packets are transmitted during the DP1 transmission phase if the measured channel load is high.
- The resulting overall duty cycle might be slightly higher than the duty cycle limit for DP3 packets as DP1 and CAMs are transmitted without duty cycle limitations. Nevertheless, the impact is small as long as the DP1 transmissions are strongly restricted to emergency situations.
- Duty cycle limitations for each vehicle contributes to the coexistence of C-ITS and services in adjacent frequency bands ITS system.

C2C communication requires small transmit delays and high position accuracy for each safety relevant applications. Hence, it is not recommended to use DCC version B. The performance of DCC variant A and C is quite similar and from a C2C system point of view, they could be both used. Nevertheless, coexistence of C-ITS system might favour a duty cycle limitation, which is supported by DCC variant C.

⇒ **Select DCC variant C for optimization**

6 Optimisation of the selected DCC variant

6.1 Target

The simulations in section 5.2 have shown that the positioning error in DCC variant C is slightly worse than DCC variant A for medium to high system loads. It is expected that larger CAM packet time intervals in DCC variant C for channel loads above 42% (see Figure 3-5) are the reason for the degradation. Hence, the impact of packet interval reduction for DCC variant C on the system performance is investigated in the first subsection.

The second part of this section aims to reduce the channel load in high density scenarios in order to decrease the packet collision rate. This will be done by tightening the transmit rules for DP3 packets. Nevertheless, DP3 packet forwarding is required to spread emergency messages over distances larger than the radio range. Hence, the number of vehicles receiving at least one copy of an emergency packet should not be significantly smaller using the new parameter setting.

6.2 Simulation results

6.2.1 Position error

The original CAM packet intervals of DCC variant C are replaced by a modified parameter set shown in the table below. The CAM distance is now upper limited by 250 ms, corresponding to the maximum value in DCC variant A.

	Relaxed	**Active1**	**Active2**	**Active3**	**Active4**	**Active5**	**Restrictive**
Channel Load	[0%, 19%[	[19%, 27%[	[27%, 35%[	[35%, 43%[	[43%, 51%[	[51%, 59%[	≥59%
DP2 (org)	100 ms	140 ms	180 ms	220 ms	260 ms	300 ms	340 ms
DP2 (mod)	100 ms	140 ms	180 ms	220 ms	**250 ms**	**250 ms**	**250 ms**

Table 6-1: Minimum packet distances in DCC variant C for DP2 packet in original and modified version

Then the number of transmitted packets and their delays in MAC and DCC are compared for the original and the modified DCC variant C. As the modifications only belong to congested DCC states the results are almost identical for the low traffic load scenario with 128 vehicles as shown in Table 6-2.

DP1	DP1 (org)	DP1 (mod)	CAM (org)	CAM (mod)	DP3 (org)	DP3 (mod)
TxRequest	19.2	19.2	457.0	458.0	4359.3	4384.7
TxPacket	19.2	19.2	457.0	458.0	108.2	107.8
RxPacket	1469	1472	31232	31314	6118	6085
$\bar{d}_{DCC}$[s]	0	0	0	0	0.12	0.12
$std(d_{DCC})$ [s]	0	0	0	0	0.15	0.14
$\hat{d}_{DCC}$[s]	0	0	0	0	1.08	1.01
$\bar{d}_{MAC}$[ms]	0.30	0.32	0.64	0.66	1.26	1.28
$std(d_{MAC})$ [ms]	0.38	0.38	1.05	1.05	1.70	1.71
$\hat{d}_{MAC}$[ms]	1.56	1.61	8.48	8.12	9.65	9.47

Table 6-2: DCC variant C in the original and modified version, 128 vehicles

A small impact on the number of transmitted packets can be observed for medium loads. The number of transmitted CAMs increases by 2%, while the number of transmitted DP3 decreases by 1.6%, respectively.

DP1	DP1 (org)	DP1 (mod)	CAM (org)	CAM (mod)	DP3 (org)	DP3 (mod)
TxRequest	20.2	20.2	386.9	397.4	5031.9	4954.0
TxPacket	20.2	20.2	386.9	397.4	82.4	81.1
RxPacket	1884	1909	36290	37580	5782	5645
$\bar{d}_{DCC}$[s]	0	0	0	0	0.12	0.13
$std(d_{DCC})$ [s]	0	0	0	0	0.16	0.16
$\hat{d}_{DCC}$[s]	0	0	0	0	1.03	0.98
$\bar{d}_{MAC}$[ms]	0.51	0.51	0.84	0.89	1.67	1.71
$std(d_{MAC})$ [ms]	0.55	0.57	1.36	1.42	2.46	2.45
$\hat{d}_{MAC}$[ms]	2.34	2.47	11.17	11.73	14.36	13.61

Table 6-3: DCC variant C in the original and modified version, 256 vehicles

As expected the largest differences are measured in the scenario with 512 vehicles. The smaller CAM packet intervals increase the number of CAMs by 8%.On the other side, the higher duty cycle for DP2 packets lowers the number of transmitted DP3 by 5.8%.

DP1	DP1 (org)	DP1 (mod)	CAM (org)	CAM (mod)	DP3 (org)	DP3 (mod)
TxRequest	19.7	19.7	330.4	357.0	5104.9	4802.9
TxPacket	19.7	19.7	330.4	357.0	64.3	60.8
RxPacket	2171	2100	40563	43811	5499	5014
$\bar{d}_{DCC}$[s]	0.00	0.00	0.00	0.00	0.14	0.15
$std(d_{DCC})$ [s]	0.00	0.00	0.00	0.00	0.18	0.20
$\hat{d}_{DCC}$[s]	0.00	0.00	0.00	0.00	1.00	1.08
$\bar{d}_{MAC}$[ms]	0.61	0.62	1.23	1.33	3.08	3.44
$std(d_{MAC})$ [ms]	0.67	0.68	2.15	2.11	5.21	4.79
$\hat{d}_{MAC}$[ms]	3.01	3.02	20.55	17.96	31.20	24.93

Table 6-4: DCC variant C in the original and modified version, 512 vehicles

Nevertheless, the changes are still not dramatic, but they are sufficient to achieve a position error for DCC variant C, which is almost identical to the performance of the original DCC variant A. A comparison of the position error based on transmitted CAMs are summarised below.

Position Error	128 (variant A)	128 (variant C, org)	128 (variant C, mod)
mean	5.40	5.30	5.29
standard deviation	1.49	1.43	1.42
max	10.07	10.46	9.94

Position Error	256 (variant A)	256 (variant C, org)	256 (variant C, mod)
mean	6.15	6.23	6.06
standard deviation	1.71	2.00	1.71
max	10.57	13.98	10.49

Position Error	512 (variant A)	512 (variant C, org)	512 (variant C, mod)
mean	6.66	7.13	6.57
standard deviation	1.67	2.28	1.68
max	10.99	14.88	12.20

Table 6-5: Position errors based on CAM transmissions for the original and the modified DCC variant C and 128, 256 and 512 vehicles

A similar performance improvement can be observed comparing the CDF functions of the position error based on CAM receptions for the original and modified DCC variant C. The modified version outperforms the results with the original DCC variant C and becomes almost identical to the results with DCC variant A. A higher number of vehicles have positions errors below 10 m for medium and high traffic loads.

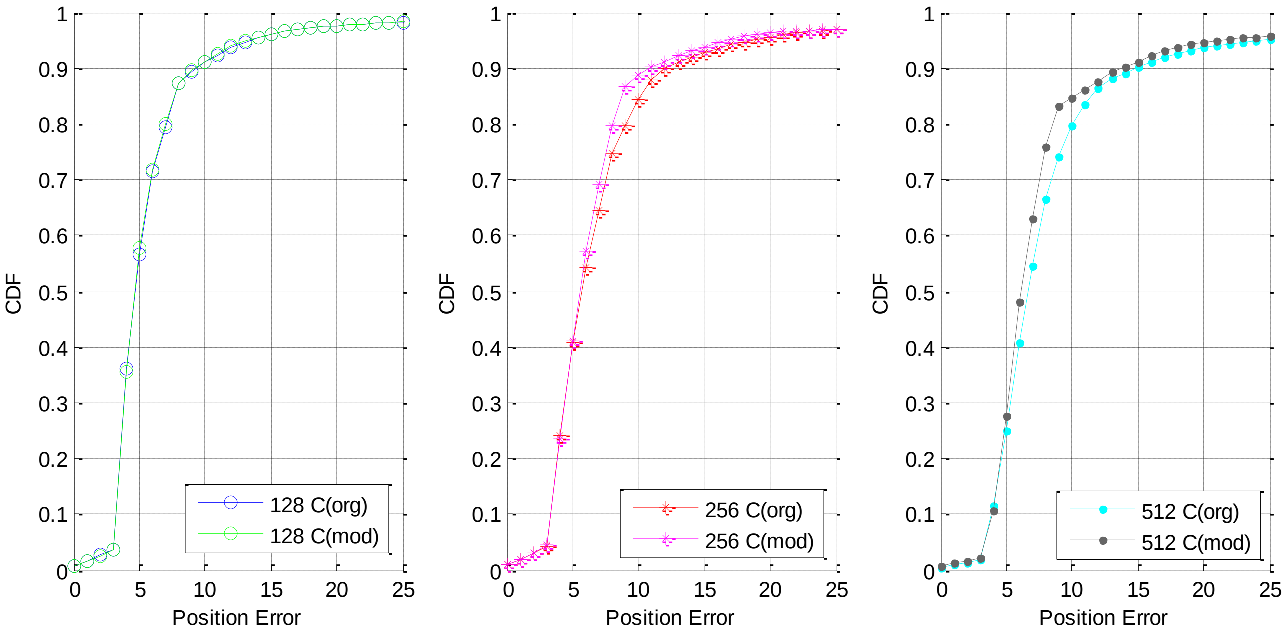


Figure 6-1: CDF of the position error based on CAM receptions for the original and the modified DCC variant C and 128, 256 and 512 vehicles

6.2.2 Optimisation of the DP3 transmit limits

DP3 packets are required to forward emergency packets to vehicles outside the radio range of the original transmitter. Nevertheless, the number of DP3 packets should be as small as possible to reduce the channel load. Channel load and packet collision rate are investigated for different DP3 transmit parameter setting as it has been already done in section 5.2 for DCC variant A, B and C.

Additionally, the number of vehicles will be counted which do not receive any copy of an emergency packet. This analysis is done as follows: Half of the vehicles in the simulations are travelling in the upstream direction (i.e. direction where the crashed car blocks the road after 20s). They are all transmitting an emergency packet. Each 'traffic jam' and the 'post-crash' message has its specific packet number *p*, which is assigned by the originator of the emergency message. This packet number is maintained for all repetitions and during packet forwarding. A counter $N(p,k)$ records the number of copies of packet *p* received at vehicle *k*:

$N(p,k)$: Number of copies of packet *p* received by vehicle *k*
with $1 \le p \le \dfrac{N_{vehicles}}{2}$
and $1 \le k \le N_{vehicles}$

The number of vehicles receiving no or only one copy of the emergency packet should be as small as possible for safety reasons. On the other side the mean number of received copies should be not unnecessarily high. The total number of incidents that a vehicle receives either none or only one copy of an emergency packet and the mean number of received packets can be calculated as follows:

$$N_o = \sum_{p=1}^{N_{vehicles}/2} \sum_{k=1}^{N_{vehicles}} (N(p,k) == 0)$$

$$N_1 = \sum_{p=1}^{N_{vehicles}/2} \sum_{k=1}^{N_{vehicles}} (N(p,k) == 1)$$

$$N_{mean} = \frac{2}{N_{vehicles}^2} \sum_{p=1}^{N_{vehicles}/2} \sum_{k=1}^{N_{vehicles}} N(p,k)$$

In summary, different DP3 parameter setting will be compared with regards to

- the resulting channel load
- the packet collision rate
- the number of occurrences (N_o) that a vehicle receives no copy
- the number of occurrences (N_1) that a vehicle receives only one copy
- the mean number of received copies per emergency packet

The triggering condition generates no DP1 packets with a packet rate higher than the lowest packet rate allowed in the DCC, so that the DCC has no impact on DP1 packet transmissions. For DP3 packets only the duty cycle is modified keeping the minimum packet distance constant. The following parameter settings for DP2 and DP3 will be compared:

C0: DCC variant C, original:

	Relaxed	Active1	Active2	Active3	Active4	Active5	Restrictive
DP2	100 ms	140 ms	180 ms	220 ms	260 ms	300 ms	340 ms
DC_{max}	1%	0.9%	0.8%	0.7%	0.6%	0.5%	0.4%

C1: DCC variant C, improved position error (see section 6.2.1):

	Relaxed	Active1	Active2	Active3	Active4	Active5	Restrictive
DP2	100 ms	140 ms	180 ms	220 ms	250 ms	250 ms	250 ms
DC_{max}	1%	0.9%	0.8%	0.7%	0.6%	0.5%	0.4%

C2: DCC variant C, lowered duty cycle:

	Relaxed	Active1	Active2	Active3	Active4	Active5	Restrictive
DP2	100 ms	140 ms	180 ms	220 ms	250 ms	250 ms	250 ms
DC_{max}	1%	0.9%	0.8%	0.65%	0.5%	0.3%	0.1%

C3: DCC variant C, lowered duty cycle:

	Relaxed	Active1	Active2	Active3	Active4	Active5	Restrictive
DP2	100 ms	140 ms	180 ms	220 ms	250 ms	250 ms	250 ms
DC_{max}	1%	0.85%	0.7%	0.55%	0.4%	0.25%	0.1%

C4: DCC variant C, lowered duty cycle:

	Relaxed	Active1	Active2	Active3	Active4	Active5	Restrictive
DP2	100 ms	140 ms	180 ms	220 ms	250 ms	250 ms	250 ms
DC_{max}	1%	0.8%	0.6%	0.4%	0.2%	0.15%	0.1%

Table 6-6: Different parameter setting proposed for DCC variant C

Differences to the previous setting are marked in red. Simulations are performed for low (128 vehicles), medium (256) and high (512) number of vehicles on the simulated highway section. Results for packet collision rates and channel load are only shown for the post-crash phase. The first table summarises the results for the low traffic scenario with 128 vehicles.

	DCC variant	C0	C1	C2	C3	C4
Packet collision rate	mean [%]	20.1	20.0	20.0	19.4	18.2
	median [%]	19.4	19.4	19.4	18.7	17.6
	std [%]	5.3	5.2	5.3	5.0	4.8
Channel load	mean [%]	35.0	34.9	34.8	33.9	30.5
	median [%]	35.0	34.8	34.8	33.8	30.2
	std [%]	9.2	9.2	9.2	9.0	8.4
	N_o	0	0	0	1 (0.012%)	0
	N_1	0	0	0	2 (0.025%)	4 (0.05%)
	N_{mean}	118.5	118.1	117.1	111.8	88.2

Table 6-7: Performance parameters for 128 vehicles

The performances of the original DCC variant C (C0) and its first modification with the CAM packet interval limitation (C1) are almost identical. The mean packet collision rate is 20% caused by a mean channel load of 35%- Each vehicles receives in the average 118 copies of an emergency packet, while the minimum number of packets is at least two, as both N_1 and N_0 are zero. Decreasing the maximum duty cycle for DP3 packet transmissions allows to reduce the channel load by up to 4.5% for setting C4. The corresponding mean packet collision rate is lowered by 2%. As desired the mean number of transmitted packets decreases to 88, but four times (0.05%) only one copy of an emergency packet is received.

The effect of duty cycle limitations in medium and high density situations are summarized in Table 6-8 and Table 6-9, respectively. For the highway scenario with 256 vehicles the mean packet collision rate successively drops from 29% to 24.5% as a result of a smaller mean channel load, which decreases from 42% to 35%. As desired the mean number of copies for an emergency packet drops from 60 to 39, but on the other side the probability that a vehicle receives no copy of an emergency packet increases from 0.2% to 2.6%.

	DCC variant	C0	C1	C2	C3	C4
Packet collision rate	mean [%]	29.0	28.9	28.1	27.5	24.5
	median [%]	26.0	26.1	25.2	24.8	22.1
	std [%]	8.8	8.9	8.8	8.5	7.7
Channel load	mean [%]	42.2	42.6	40.7	39.7	35.3
	median [%]	41.8	42.2	40.1	30.1	34.7
	std [%]	11.5	11.6	11.0	11.0	9.8
	N_o	65 (0.2%)	76 (0.23%)	112 (0.34%)	197 (0.60%)	853 (2.6%)
	N_1	61 (0.19%)	61 (0.19%)	194 (0.59%)	163 (0.50%)	558 (1.7%)
	N_{mean}	59.9	59.0	53.9	51.6	39.2

Table 6-8: Performance parameters for 256 vehicles

The largest impact is observed for the high density scenario. The mean channel load in the post-crash phase drops from 50% to 40% reducing the packet collision rate by 7%. The mean number of received packet drops from 31 to 17.5 at the cost of a significantly higher probability for a reception failure of 21% for the lowest duty cycle limits compared to 3.7% for the original DCC variant.

	DCC variant	C0	C1	C2	C3	C4
Packet collision rate	mean [%]	37.5	38.5	35.4	33.8	30.6
	median [%]	33.4	34.2	31.6	30.1	27.3
	std [%]	11.9	12.1	11.1	11.0	10.5
Channel load	mean [%]	50.4	51.4	46.6	45.2	40.9
	median [%]	49.9	51.0	46.1	44.5	40.2
	std [%]	14.9	15.2	12.0	13.1	12.3
	N_o	4887 (3.7%)	7419 (5.7%)	14616 (11.2%)	15680 (12.0%)	27351 (20.9%)
	N_1	3136 (2.4%)	3668 (2.8%)	4633 (3.5%)	4976 (3.8%)	5773 (4.4%)
	N_{mean}	31.2	28.9	24.1	22.7	17.5

Table 6-9: Performance parameters for 512 vehicles

6.2.3 Conclusions

The position error using the original parameter settings for DCC variant C has been slightly worse compared to DCC variant A for high vehicle densities. The position accuracy can be easily improved limiting the minimum DP2 packet interval at high DCC states to 250 ms (same value is used by DCC variant A). The higher number of CAM transmissions slightly lowers the number of transmitted DP3 packets, so that the mean number of received copies of the same emergency packet is reduced and the probability increases to receive no copy at all. Nevertheless, the effect is quite small and the improved position accuracy might be more interesting with regards to the overall C2C system performance.

Comparing the number of transmitted DP1, DP2 and DP3 packets in all simulations shows that a significant amount of traffic is generated by packet forwarding (DP3 packets). One reason is certainly the large relevance area and the high number of hops specified by the two use cases. Additionally, the duplicate packet detections in the packet forwarding algorithm (Annex E.3 [7]) might have problems if vehicles are closely located. Hence, simulations have been done using different duty cycle limits for DP3 packets in order to reduce the number of DP3 packet transmissions. Nevertheless, smaller duty cycle limits always increase the probability that no copy of an emergency packet is received, although the average number of received copies is still quite high. The problem of inhomogeneous packet delivery cannot be solved by the DCC access layer. Much more information is available in the GeoNetworking layer like the number of neighbours in close vicinity, which might be used to optimise the forwarding. Nevertheless, it has to be taken into account that the number of emergency messages in the simulation is probably much higher than in reality. In the simulation, each vehicle approaching the traffic jam generates its own emergency message. This is certainly a worst case scenario, but allows reducing the number of vehicles for a high channel load scenario. It is expected that the number of DP1 and DP3 packet transmissions per vehicle will be typically smaller in a real traffic jam situation and the duty cycle limits as specified in C3 might a good compromise to start in day1.

7 Summary and recommendations

The performance of three different implementations of the DCC access functionalities has been compared in a highway scenario with CAM and DENM transmissions at different vehicle densities. The two DCC variants proposed in the DCC white paper v0.5 [4] and version 1.1 [2] are implemented as DCC variant A and B. A third alternative called DCC variant C is proposed, which uses parts of DCC variant A, e.g. the priority specific DCC queue control, and of DCC variant B, e.g., channel load thresholds, and applies an additional transmit duty cycle limitation to low priority packets.

All three variants in principle succeed to limit the channel load even at high vehicle densities. Channel loads and packet collision rates are quite comparable; only for high vehicle densities the transmission constraints of DCC variant B are slightly more restrictive. Nevertheless, the common transmit control for DP1, DP2 and DP3 packets in DCC variant B introduces considerable delay in the DCC layer in case packets of different priority are transmitted simultaneously. The result is a latency for high priority DENMs and a decrease of position accuracy as detailed below. This was the main reason to skip DCC variant B in section 5.3. In principle, there are almost no performance difference between DCC variant A and C. Nevertheless, coexistence of C-ITS and services in adjacent frequency bands ITS system might be complicated by the fact that DP3 packet transmissions are scheduled independent on higher priority packet transmissions in DCC variant A. This might lead to high peak duty cycles in case the measured channel load decreases within a short time. DCC variant C solves this problem defining an additional duty cycle limitation to DP3 packets transmissions. Hence, DP3 packets are just transmitted if the transmit duty cycle of all priority packet transmissions is below a certain threshold.

It is recommended to use DCC variant C with additional duty cycle limitations for DP3 packets

General recommendations:

DP0/DP1 packets:

The transmission of high priority packets (DP0/DP1) should be restricted to emergency situations only. As they contain safety relevant information, these packets need to be delivered with high reliability and low latency. High reliability in a broadcast system generally means that packets are repeated or retransmitted with an updated content in order to cope with packet losses. Nevertheless, update intervals as well as repetitions need to be carefully designed, especially if multi-hop forwarding is required to extend the coverage area. In this case, each high priority packet transmission triggers an amount of DP3 packet forwards, which might results in a significant increase of the channel load (see also DP3 packets below).

Hence, DP0/DP1 packet transmissions should be restricted, but it is recommended to shift the transmit control to the application layer instead of using the DCC access. The reason is that even the day one use cases have quite different requirements with regards to latency, validity duration, update intervals and relevance area. There are “Post-crash” warnings with large retransmission intervals and a huge relevance area requiring the maximum number of hops for packet forwarding. On the other side, a “Collision risk” warning is only dedicated for one specific vehicle in the radio range and requires low latency communication.

In general it seems to be reasonable to use a higher minimum packet distance for messages with a large coverage area as they have a significant impact on the channel load due to the multi-hop forwarding. On the other side, a short term communication among two vehicles does not need any forwarding and shorter packet distances could be allowed. Hence, it is very difficult to define one appropriate minimum packet distance for all types of DP0/DP1 packets, which would be required when implementing transmit control in the DCC access.

It is therefore proposed to let the DP0/DP1 packets pass the DCC access layer without any delay and to apply duty cycle limits and minimum packet distances in the application layer. This is exactly what DCC variant A and C has been done in the simulations as the DCC layer allows for a higher packet rate as it has been required by the application. The duty cycle for the “traffic jam ahead” and the “post crash” use cases considered in the highway simulation has been 0.43% for 20 s or 0.2% for 60 s, respectively. Hence a duty cycle of 0.1-0.2 % within a measurement time of 1 minute and a minimum packet distance of 500 ms could be appropriate values for emergency packets with the maximum number of hops and large coverage area. Limits for other DP0/DP1 packet types might be different and needs to be defined.

⇨ It is recommended to shift the transmit control for DP0 and DP1 packets to the application layer

DP2 packets:

If position information is only transmitted in CAM packets[2], it is not reasonable to increase the CAM packet interval in the presence of DP1 packet transmissions as it is done in DCC method B. DP1 packets are only transmitted in emergency situations where an exact knowledge of the transmitter position might be even more important than in a standard situation. It is one advantage of DCC variant A and C to send CAMs independent on other priority packet transmissions.

Nevertheless, the main advantage of DCC variant A and C is that CAMs are transmitted without any delay in the DCC. The facilities layer can be easily informed on the current minimum DP2 packet distance, so that the CAM always contains the actual position information. In DCC variant B CAMs have been significantly delayed during the DP1 transmission phase resulting in higher position errors. It should be taken into account that the “traffic jam ahead” warning is only transmitted at low vehicles speeds below 30 km/h. Hence, the position error introduced by the delay of the CAM is significantly smaller than it would be for a vehicle travelling with high speed. The performance of DCC variant B could be significantly worse in other use cases.

⇨ Use a separate DCC queue for CAMs and inform the facility layer on the current minimum distance to avoid any delay in the DCC

[2] In case DP0/DP1 will deliver position information in the future, a new functionality could be added to the facilities layer to reduce CAM transmit intervals during DENM transmissions.

DP3 packets:

In the simulations, a large amount of DP3 packets is generated by the packet forwarding algorithm specified in Annex E.3 [7]. Each vehicle typically receives in the average tens of copies of the same emergency message. Using smaller duty cycle limits for DP3 packet transmissions lowers the mean number of copies, but increases the number of vehicles which do not receive any copy of an emergency packet. Hence, it is difficult to solve the problem in the DCC access. An analysis of the forwarding algorithm has been out of the scope of this work, but it has been observed, that often the same packet is forwarded by a number of vehicles and duplicate packet detection fails especially in situations, where vehicles are placed within short distance (e.g. in a traffic jam, see note at the end of section 5.1.3). Furthermore, some ping-pong behaviour has been found; packets are returning to the originator after one hop. Nevertheless, a detailed analysis would be necessary to identify the problem and the other proposed forwarding concepts might works quite well.

Check if the forwarding algorithm minimizes the number of packet forwards

Additionally, packet forwarding could be significantly reduced, if the relevancy area is properly defined. For example, it might be reasonable to forward “traffic jam ahead” packets only by those vehicles positioned behind the traffic jam.

Make sure that the use cases are properly defined, e.g. the relevance area and the number of hops should as small as possible

8 Appendix 1 – References

8.1 List of abbreviations

CAM	Cooperative Awareness Message
CCA	Clear Channel Assessment
CDF	Cumulative Distribution Function
C-ITS	Cooperative Intelligent Transport System
CL	Channel Load
CSMA	Carrier Sense Multiple Access
DC	Duty Cycle
DCC	Decentralised Congestion Control
DENM	Decentralized Environmental Notification Message
EDCA	Enhanced Distributed Channel Access
ITS	Intelligent Transport System
LOS	Line Of Sight
MAC	Medium Access Control
NLOS	Non Line Of Sight
OFDM	Orthogonal Frequency Division Multiplexing
RCS	IMST Radio Channel Simulator
RLE	IMST Radio Link Emulator

8.2 Applicable documents

[1] ETSI TS 102 687 V.1.1.1 (2011-07)

[2] C2C-CC Distributed Congestion Control (DCC) for Day One. v1.1

[3] ScenarioDesrciption.doc

[4] C2C-CC Distributed Congestion Control (DCC) for Day One. v0.5

[5] IEEE 802.11:2012: "IEEE Standard for Information Technology - Telecommunications and information exchange between systems - Local and metropolitan area networks-Specific requirements - Part 11: Wireless LAN Medium Access Control (MAC) and Physical Layer (PHY) Specifications"

[6] C2C-CC Task Force Antenna white paper. v1.0

[7] EN 302 636-4-1 V1.2.1

[8] Draft C2C-CC Basic System Standards Profile

[9] EN 302 637-2, v.1.3.0

[10] ECC Report, Compatibility studies between intelligent transport systems (ITS) in the band 5855– 5925 MHz and other systems in adjacent band, draft

[11] C.f. B. Hoffmann-Wellenhof et al., *GPS Theory and Practice*, Wien, New York: Springer Verlag, 1997

[12] Minutes „Telco of C2CCC WG SIM", 07 August 2014