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**Intelligent Transport Systems (ITS);
Cross Layer DCC Management Entity for operation
in the ITS G5A and ITS G5B medium;
Report on Cross layer DCC algorithms and performance
evaluation**

Reference

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Keywords

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Contents

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Foreword

This Technical Report (TR) has been produced by ETSI Technical Committee Intelligent Transport Systems (ITS).

Modal verbs terminology

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1 Scope

The present document provides a preliminary technical overview of the cross-layer decentralized congestion control (DCC) architecture to be implemented in the ITS-S. It describes DCC functions and testable DCC limits and includes initial performance evaluation results based on simulations. In addition, reference scenarios and parameters used for performance evaluation purposes and the corresponding evaluation metrics are summarized. It will be completed by a Technical Report with validation set-up and results. Both will serve as a basis for the Technical Specification of the Cross Layer DCC control entity in the ITS G5A and ITS G5B media.

2 References

References are either specific (identified by date of publication and/or edition number or version number) or non-specific. For specific references, only the cited version applies. For non-specific references, the latest version of the reference document (including any amendments) applies.

Referenced documents which are not found to be publicly available in the expected location might be found at http://docbox.etsi.org/Reference.

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2.1 Normative references

The following referenced documents are necessary for the application of the present document.

Not applicable.

2.2 Informative references

The following referenced documents are not necessary for the application of the present document but they assist the user with regard to a particular subject area.

[i.1] IEEE 802.11-2012: "IEEE Wireless Local Access Network - Part 11: Wireless LAN Medium Access Control (MAC) and Physical Layer (PHY) Specifications".

[i.2] ETSI TS 102 687: "Intelligent Transport Systems (ITS); Decentralized Congestion Control Mechanisms for Intelligent Transport Systems operating in the 5 GHz range; Access layer part".

[i.3] ETSI EN 302 636-4-1: "Intelligent Transport Systems (ITS); Vehicular Communications; GeoNetworking; Part 4: Geographical addressing and forwarding for point-to-point and point-to-multipoint communications; Sub-part 1: Media-Independent Functionality".

[i.4] ETSI TS 102 636-4-2: "Intelligent Transport Systems (ITS); Vehicular Communications; GeoNetworking; Part 4: Geographical addressing and forwarding for point-to-point and point-to-multipoint communications; Sub-part 2: Media-dependent functionalities for ITS-G5".

[i.5] ETSI TS 102 723-3: "Intelligent Transport Systems (ITS); OSI cross-layer topics; Part 3: Interface between management entity and access layer".

[i.6] ETSI TS 102 723-4: "Intelligent Transport Systems (ITS); OSI cross-layer topics; Part 4: Interface between management entity and networking & transport layer".

[i.7] ETSI TS 102 723-5: "Intelligent Transport Systems (ITS); OSI cross-layer topics; Part 5: Interface between management entity and facilities layer".

[i.8] ETSI TS 102 723-10: "Intelligent Transport Systems (ITS); OSI cross-layer topics; Part 10: Interface between access layer and networking & transport layer".

[i.9] ETSI TS 102 723-11: "Intelligent Transport Systems (ITS); OSI cross-layer topics; Part 11: Interface between networking and transport layer and facilities layer".

[i.10] ETSI EN 302 665: "Intelligent Transport Systems (ITS); Communications Architecture".

[i.11] ETSI EN 302 663: "Intelligent Transport Systems (ITS); Access layer specification for Intelligent Transport Systems operating in the 5 GHz frequency band".

[i.12] ETSI EN 302 571: "Intelligent Transport Systems (ITS); Radiocommunications equipment operating in the 5 855 MHz to 5 925 MHz frequency band; Harmonized EN covering the essential requirements of article 3.2 of the R&TTE Directive".

[i.13] ECC/DEC/(08)01 ECC Decision on the harmonised use of the 5875-5925 MHz frequency band for Intelligent Transport Systems (ITS).

[i.14] ETSI TS 102 792: "Intelligent Transport Systems (ITS); Mitigation techniques to avoid interference between European CEN Dedicated Short Range Communication (CEN DSRC) equipment and Intelligent Transport Systems (ITS) operating in the 5 GHz frequency range".

[i.15] ETSI TS 103 257: "Intelligent Transport Systems (ITS); Access Layer; ITS-G5 Channel Models and Performance Analysis Framework".

[i.16] M. Rondinone et al.: "iTETRIS: A Modular Simulation Platform for the Large Scale Evaluation of Cooperative ITS Applications", Simulation Modelling Practice and Theory, Volume 34, May 2013.

[i.17] M. Boban: "GEMV2: Geometry-based Efficient Propagation Model for V2V Communication", available at http://vehicle2x.net.

[i.18] G. Bansal and J.B. Kenney: "Controlling Congestion in Safety-Message Transmissions: A Philosophy for Vehicular DSRC Systems," Vehicular Technology Magazine, IEEE, vol.8, no.4, pp. 20 - 26, December 2013.

[i.19] B. Kloiber, J. Härri, T. Strang.: "Dice the TX power - Improving Awareness Quality in VANETs by Random Transmit Power Selection", IEEE Vehicular Networking Conference (VNC'12), Seoul, Republic of Korea, November 2012.

[i.20] T.Tielert, D.Jiang, L. Delgrossi, H. Hartenstein, "Design methodology and evaluation of rate adaptation based congestion control for vehicle safety communications," IEEE Vehicular Networking Conference (VNC '11), Amsterdam, Netherlands, Nov. 2011.

3 Definitions, symbols and abbreviations

3.1 Definitions

For the purposes of the present document, the terms and definitions given in IEEE 802.11-2012 [i.1], ETSI EN 302 665 [i.10], ETSI EN 302 663 [i.11], ETSI EN 302 571 [i.12] and the following apply:

adaptability: performance characteristic, which indicates that a system is capable of adjusting its parameters to maintain the same level of performance when the input conditions are changing

CBR evaluation: function that transforms the hardware specific CL value into a hardware independent local CBR value

channel access time: variable representing the time for an ITS-S to access the channel and send a packet.

channel busy ratio: time-dependent value between zero and one (both inclusive) representing the fraction of time that the channel was busy

NOTE: this is one implementation of the channel load metric.

channel load: reference metrics, ranging between 0 and 1, which represents the relative quality of the channel. The higher the load on the channel, the less reliable the reception of the transmitted message is

NOTE: This value is an indication for the channel usage, provided by the radio hardware.

channel resource limit: maximum amount of usable resources of a channel. It corresponds to a trade-off between the maximum usage of the channel for periodic safety-related messages, maximizing the performance of the ITS-G5 technology and allowing any event-based emergency packet to be reliably transmitted

communication range: maximum Euclidian distance from the sender where a communication can take place with a message reception rate of more than 95 %

cross-layer DCC: cooperation mechanisms based on components distributed over several layers of the protocol stack which jointly work together to fulfil the operational requirements of DCC

DCC_ACC: DCC gatekeeper component located at the Access Layer

DCC channel switching indication: indication sent to the DCC functions at upper layers in the case where a message has been switched to a channel different from the one initially requested

DCC channel switching parameter: parameter indicating to which other channels a message may be rerouted in case the channel initially planned is congested **DCC_FAC:** DCC component located at the facilities layer

DCC_CROSS: DCC cross-layer component located in the management plane

DCC_CROSS_Access: function in the DCC_CROSS component that provides DCC control parameters to DCC_ACC

DCC_CROSS_Facilities: function in the DCC_CROSS component that provides DCC control parameters to the facilities layer and to the applications Layer

DCC_CROSS_Net&Tr: function in the DCC_CROSS component that provides DCC channel switching parameters to the networking and transport layer and a DCC channel switching indication to the DCC_CROSS_Facilities

DCC fairness: a concept where any ITS-S under the same channel conditions have an equal opportunity of accessing the channel for periodic messages, while maintaining a channel access margin to always allow the exchange of safety-critical event-based messages

DCC flow control: function that retrieves the messages from the DCC queues according to their priorities and transfers them for transmission to the ITS-G5 radio functionalities

DCC flow control parameters: DCC parameters generated by the DCC_CROSS_Access that indicate to the DCC flow control the amount of usable resources available for transmission on the radio

DCC_NET: DCC component located in the networking & transport layer

DCC parameter evaluation: function that takes the local CBR and the global DCC RX parameters as input and evaluates them to obtain the internal DCC parameters and the global DCC TX parameters

DCC power control: optional function that sets the ITS-G5 TX power level according to the DCC power control parameters

DCC power control parameters: DCC parameters generated by the DCC_CROSS_Access function to set the ITS-G5 TX power level limits

DCC prioritization: function that routes messages per channel to DCC queues according to the IEEE 802.11 [i.1] EDCA access category indicated in the traffic class field

DCC queues: set of buffer space in the DCC_ACC component in the access layer that stores the transmission requests sorted according to their priority (access class)

NOTE: A DCC queue retains a message, if a message in a DCC queue with higher priority is present.

decentralized congestion control: set of mechanisms for ITS-S to maintain network stability, throughput efficiency and fair resource allocation to ITS-Ss using ITS-G5 access technology

global channel busy ratio: maximum value of the local channel busy ratio, the 1-hop channel busy ratio and the 2-hop channel busy ratio

global DCC RX parameters: DCC parameters received from neighbouring ITS-S (e.g. their local CBR measurement) and locally determined parameters (e.g. number of neighbours) that are used to derive the currently available channel resources and the global DCC TX parameters

NOTE: These parameters comprehend the basic metrics to derive the current level of resource usage in order to classify the congestion. Metrics based on local knowledge are used in a first step, such as the Channel Busy Ratio (CBR) and the number of neighbouring ITS-S. To avoid channel congestion, it is appropriate to also use cooperatively determined metrics that can be retrieved by exchanging the local metrics.

global DCC TX parameters: DCC parameters broadcasted to neighbouring ITS-S

internal DCC parameters: management parameters that are used to disseminate the DCC parameter evaluation result to DCC_CROSS_Facilities, to DCC_CROSS_Net&Tr and to DCC_CROSS_Access

NOTE: Internal DCC parameters are derived by the DCC parameter evaluation function based on the DCC RX parameters and the local CBR value. These parameters define how much channel resources an ITS-S is allowed to use.

inter-reception rate: receiver-based metric representing the time between the successful reception of two CAM messages

NOTE: As the receiver knows the time between two CAM messages, inter-reception rate indicates message losses impacting the ITS-S safety applications.

local channel busy ratio: time-dependent value between zero and one (both inclusive), representing the channel busy ratio (CBR) as perceived locally by a specific ITS-S

message generation parameters: parameters that inform the components in the facilities layer and in the applications Layer about the available channel resources

neighbour density: metric illustrating the average number of ITS-S per square meter in the communication range of an ITS-S

resilience: performance characteristic, which indicates that a system is capable of providing a sufficient level of performance under certain conditions

responsiveness: performance characteristic, which indicates that a system is capable of adjusting its parameters fast enough to maintain a certain level of performance to sudden, brief and recurring changes in the input conditions

RSSI/RCPI: indication of the received signal power level at the receiver

NOTE: RSSI/RCPI is a receiver-centric metrics that indicates the distance to the transmitter as well as the potential impact of interfering radio signals.

scalability: performance characteristic, which indicates that a system is capable of keeping the level of performance while increasing the number of participating ITS-S

TTT Road Tolling: radio interface specified at CEN mainly for road tolling applications

NOTE: Formerly referred to as CEN DSRC.

3.2 Symbols

For the purposes of the present document, the following symbols apply:

CR_{limit} Channel Resources Limit
CBR_{limit} Channel Busy Ratio Limit
CBR^{target} Target Channel Busy Ratio
N_{Sta} Number of ITS-Ss
P_{TX} Transmit Power
R_{limit} Message Rate Limit
R^{tx} Transmit Rate
R_M Message Rate

T_{off}	Time during which a DCC queue is closed (OFF), in order to regulate congestion from the DCC queue; also considered to be the idle time for the DCC flow control function
T_{on}	Time during which a DCC queue is open (ON) and messages from the DCC queues are sent to the ITS-G5 radio also considered to be the message transmit duration for the DCC flow control function
$Toff_{limit}$	Idle Time Limit

3.3 Abbreviations

For the purposes of the present document, the following abbreviations apply:

ACC-XDCC	DCC_CROSS_Access
AI	Adaptive Increase
AIMD	Additive Increase Multiplicative Decrease
ANPI	Average Noise Power Indicator
C2X	Car-to-X communication system
CAM	Cooperative Awareness Message
CAT	Channel Access Time
CBR	Channel Busy Ratio
CCH	Control Channel
CEN	Commité Européen de Normalisation
CL	Channel Load
CR	Communication Range
CS	Carrier Sensing
CSMA/CA	Carrier Sense Multiple Access with Collision Avoidance
DCC	Decentralized Congestion Control
DENM	Decentralized Environmental Notification Message
DSRC	Dedicated Short Range Communication
DTN	Delay Tolerant Networks
DUT	Device Under Test
DVB-H	Digital Video Broadcast - Handheld
EDCA	Enhanced Distributed Channel Access
FA	Facility Layer-Application Layer
FAC-XDCC	DCC_CROSS_Facilities
GN	GeoNetworking
IDR	Information Dissemination Rate
IRT	Inter-Reception Time
ITS	Intelligent Transportation System
ITS-S	ITS Station
KPI	Key Performance Indicator
LOS	Line-of-Sight
MD	Multiplicative Decrease
NET-XDCC	DCC_CROSS_Net&Tr
NLOS	Non Line-of-Sight
OFDM	Orthogonal Frequency Division Multiplexing
OBU	On-Board Unit
PDA	Personal Digital Assistant, e.g., smartphone
QPSK	Quadrature Phase Shift Keying
RCPI	Received Channel Power Indicator
RF	Radio Frequency
RSNI	Received Signal-to-Noise Indicator
RSSI	Received Signal Strength Indicator
RSU	Road Side Unit
RX	Receiver
SAP	Service Access Point
SHB	Single Hop Broadcast
STA	Stations
TC	Traffic Class
TTT	Transport & Traffic Telematics
TCP	Transmission Control Protocol
TX	Transmitter
UMTS	Universal Mobile Telecommunication Systems

VT Vehicular Technology
XDCC DCC_CROSS

4 Introduction

The DCC functionality is part of the ITS station (ITS-S) reference architecture given in ETSI EN 302 665 [i.10]. A schematic description including interfaces is displayed in Figure 1. It consists of the following DCC components:

- DCC_ACC located in the Access as specified in ETSI TS 102 687 [i.2];
- DCC_NET located in the Networking and Transport as specified in ETSI TS 102 636-4-2 [i.4];
- DCC_FAC located in the Facilities;
- DCC_CROSS located in the management plane.

The components are connected through the DCC interface 1 to interface 4 as shown in Figure 1. These interfaces are mapped to the corresponding cross-layer interfaces as described in ETSI TS 102 723-3 [i.5], ETSI TS 102 723-4 [i.6] and ETSI TS 102 723-5 [i.7].

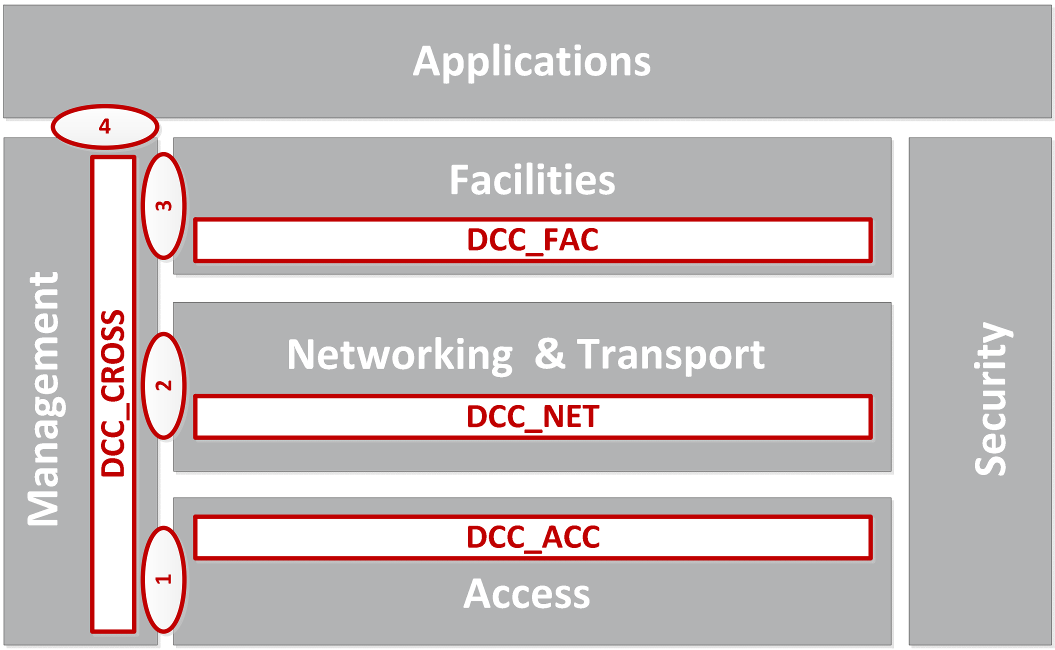

Figure 1: Overview of DCC Architecture

The present document describes the cross-layer architecture of the DCC mechanisms for ITS-G5 and focuses more specifically on the DCC management functions in the DCC_CROSS component and the DCC functions in each layer, as well as their interactions.

The present document does not specify a particular DCC algorithm to control the load on the channel between ITS-Ss; instead channel load limits are provided that all ITS-Ss need to follow regardless of DCC implementation.

Further, the present document proposes a set of scenarios for simulation as well as an evaluation methodology to be able to test and compare different approaches of the DCC algorithms The present document provides initial simulation results for two different DCC algorithms.

5 Architecture

5.1 Introduction

The primary objective for the DCC algorithm in the ITS-S is to calculate based on input parameters the currently allowed channel resource limit.

Four different configurations of the DCC architecture have been identified depending on if the ITS-S is operating on a single channel or multiple channels and if only local or both local and global input parameters to the DCC algorithm are present. In Table 1, the different configuration possibilities are outlined.

Table 1: The different identified DCC configurations

	Supported channels		**Input parameters**	
	Single	**Multi**	**Local only**	**Local and global**
DCC configuration 1	X		X	
DCC configuration 2	X		X	X
DCC configuration 3	X	X	X	
DCC configuration 4	X	X	X	X

The specification of the cross-layer DCC behaviour (DCC_CROSS) should support interoperability between the different DCC configurations. For all configurations, it is assumed that a measurement of the channel load (CL) is provided by the ITS-G5 radio component. This is the primary input to the DCC algorithm. The DCC entity processes the CL measurement data and feeds the DCC algorithm with a local channel busy ratio (CBR). All DCC configurations listed in Table 1 provide the local CBR value and support single channel operation. In DCC configurations 2 and 4, global parameters are also available through the use of ETSI TS 102 636-4-2 [i.4], which is the media-dependent part of the GeoNetworking (GN) protocol. By using this functionality of the GN protocol, the ITS-S can disseminate information about its local CL, the highest received CL from its neighbour ITS-S, its current message rate, output power etc., in GN single-hop broadcast (SHB) packets. When global input parameters are available those are saved in the GN location table of the GN protocol. The DCC configurations are detailed in clauses 5.2.1-5.2.4.

5.2 Configurations of the DCC architecture

5.2.1 DCC configuration 1

In DCC configuration 1, single channel and local DCC input parameters are present.

The calculation of available resources of the channel is only based on local CL measurements, transformed to internal DCC parameters and distributed to the DCC_CROSS_Facilities and DCC_CROSS_Access functions. The facilities can use the information to restrict the number of generated packets but it also gives the facilities the possibility to prioritize between different types of data traffic. If higher layers perform according to the output from the DCC algorithm, the access layer does not have to for example restrict the number of packets on the channel.

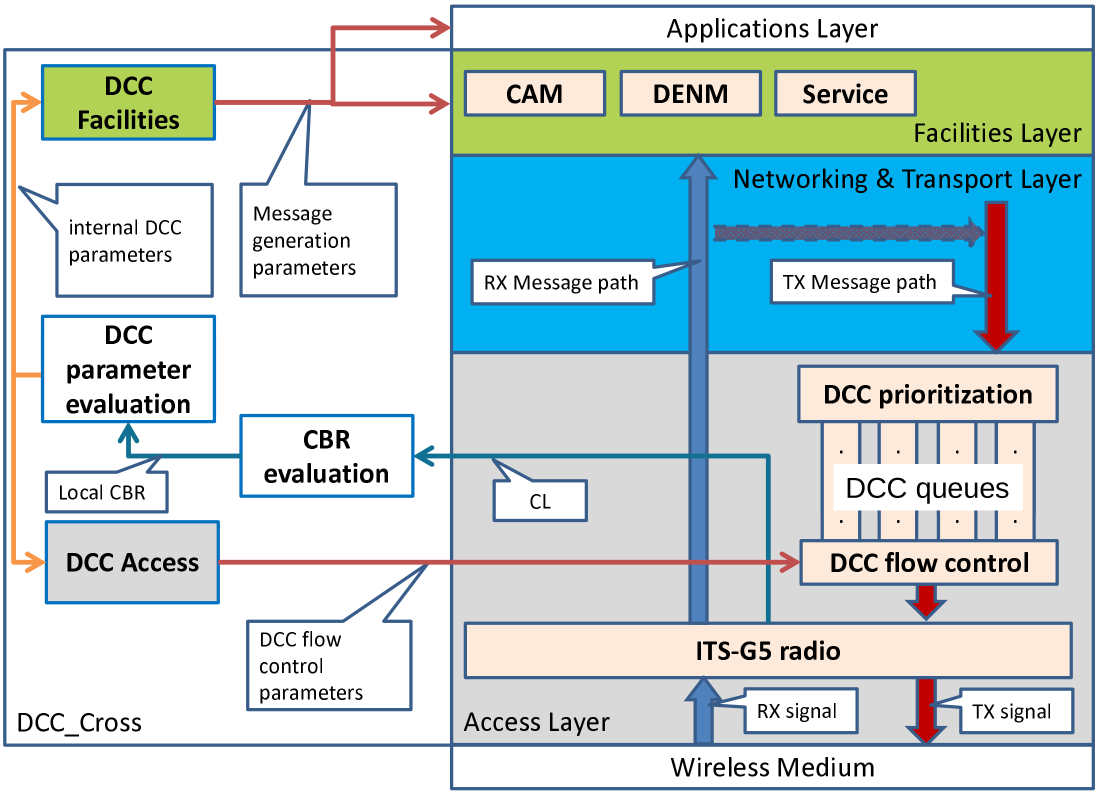

Figure 2: Architecture overview of the DCC configuration 1: Single channel operation with local DCC information

5.2.2 DCC configuration 2

In DCC configuration 2, the ITS-S only operates on a single channel but has access to global input as well as local.

Adding global DCC parameters provides the possibility to align the DCC parameters among all ITS-S in communication range (Figure 3). These parameters are stored in a neighbour table in the networking & transport. For example, ETSI TS 102 636-4-2 [i.4] specifies the dissemination of global DCC parameters and their storage in the GN location table. Together with the local CL measurement the global DCC parameters are taken as input for the evaluation of the internal DCC parameters, which are distributed and used in the same way as in the first configuration (Figure 2). Having a global DCC coordination also enables the control of the transmit power level as part of the DCC mechanism in the future. This will reduce the impact of the hidden node problem that may occur if this control is not provided.

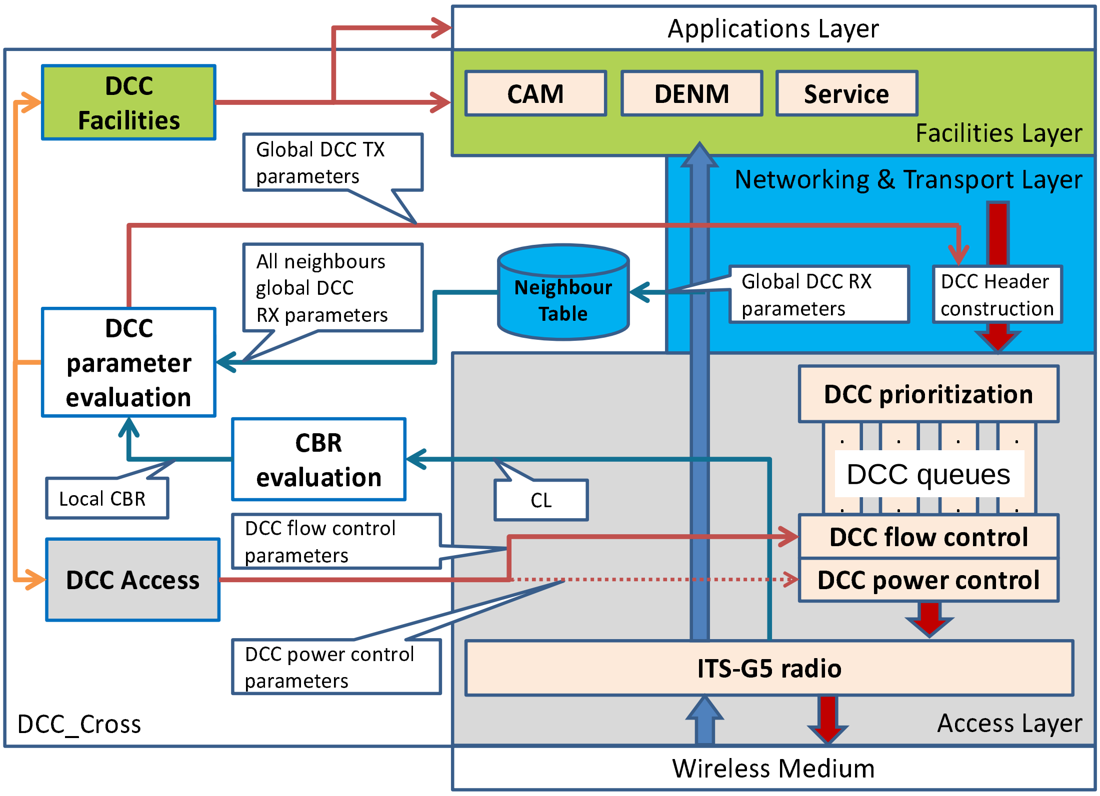

Figure 3: Architecture overview of the DCC configuration 2: Single channel with global DCC information

5.2.3 DCC configuration 3

In DCC configuration 3, the ITS-S has the capability of switching between different channels but it has only access to local DCC information.

When deploying multi-channel configurations as shown in Figure 4, the DCC mechanisms can include off-loading of messages from congested to uncongested channels. In this case, CBR measurements provided for each of the available channels by the ACC_XDCC function are used as input to the NT_XDCC function, which controls the channel switching in the networking & transport layer. Note that channel switching is possible even for a single transceiver implementation. This requires CL monitoring on all the target channels.

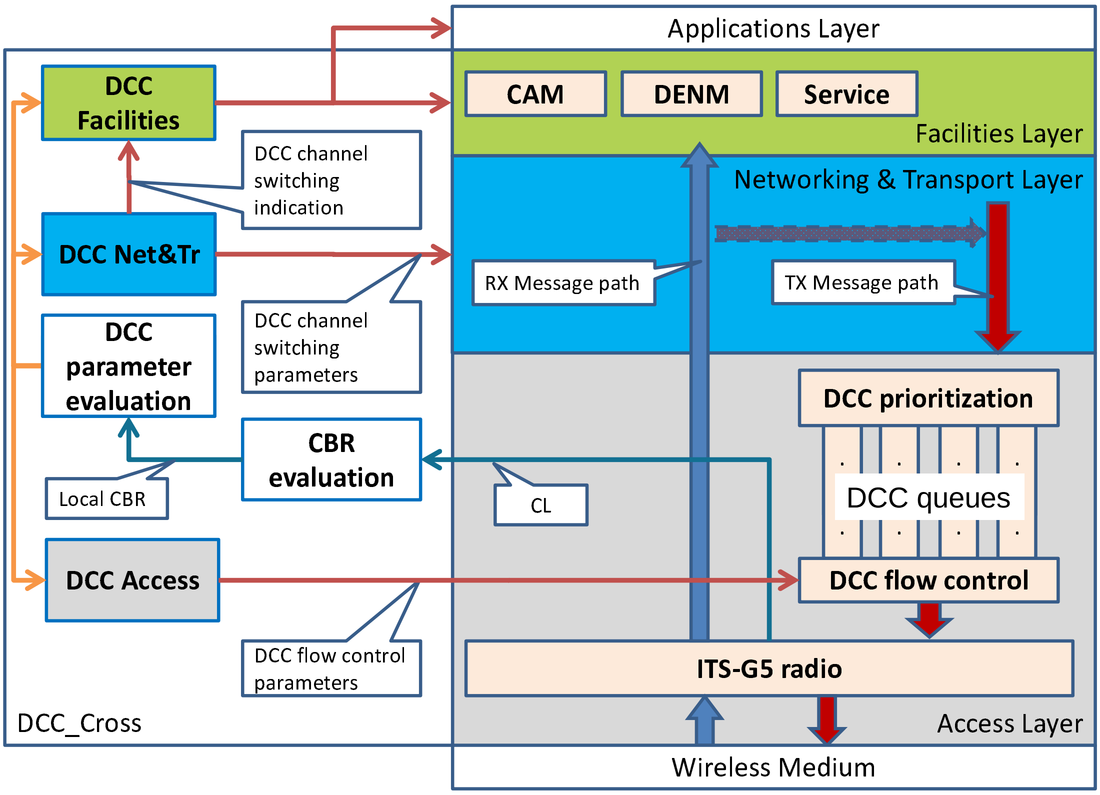

Figure 4: Architecture overview of the DCC configuration 3: Multi-channel operation with local DCC information

5.2.4 DCC configuration 4

In DCC configuration 4, the ITS-S has the capability of switching between different channels and it has access to global DCC information, see Figure 5.

In contrast to the single channel DCC parameter evaluation, the neighbour table, such as the GN location table, holds the global DCC parameters for each monitored channel. Based on these global parameters the internal DCC parameters are evaluated for each channel.

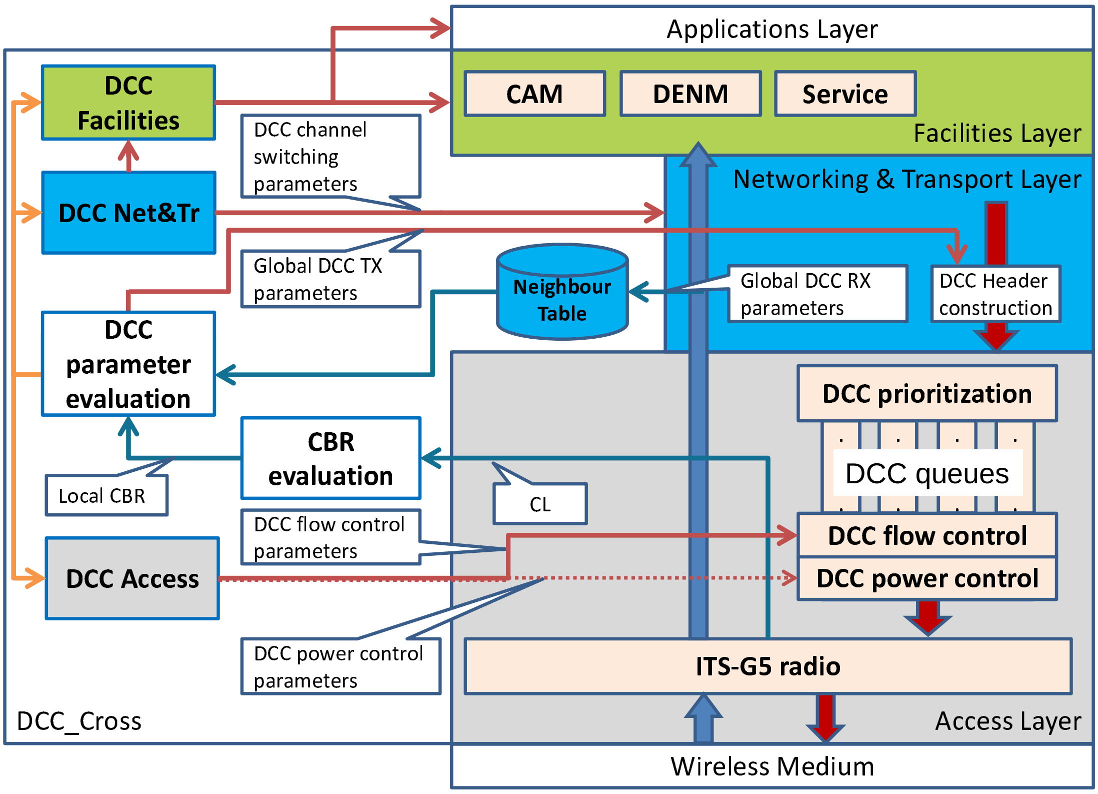

Figure 5: Architecture overview of the DCC configuration 4: Multi-channel with global DCC information

5.3 Communication stack

5.3.1 Facilities layer

The facilities layer DCC functions (DCC_FAC), included in the facilities depicted in Figure 6, control the load generated by facilities service messages (e.g. CAM and DENM) per channel. The message rate is either controlled by indicating the maximum rate to the facilities/applications, or by dropping packets that overload the channel. The DCC_FAC also potentially initiate switching between channels if the ITS-S supports this feature. Moreover, they are responsible for mapping the message priorities indicated by applications/facilities to the corresponding traffic classes. The facilities layer DCC functions are described in Table 2.

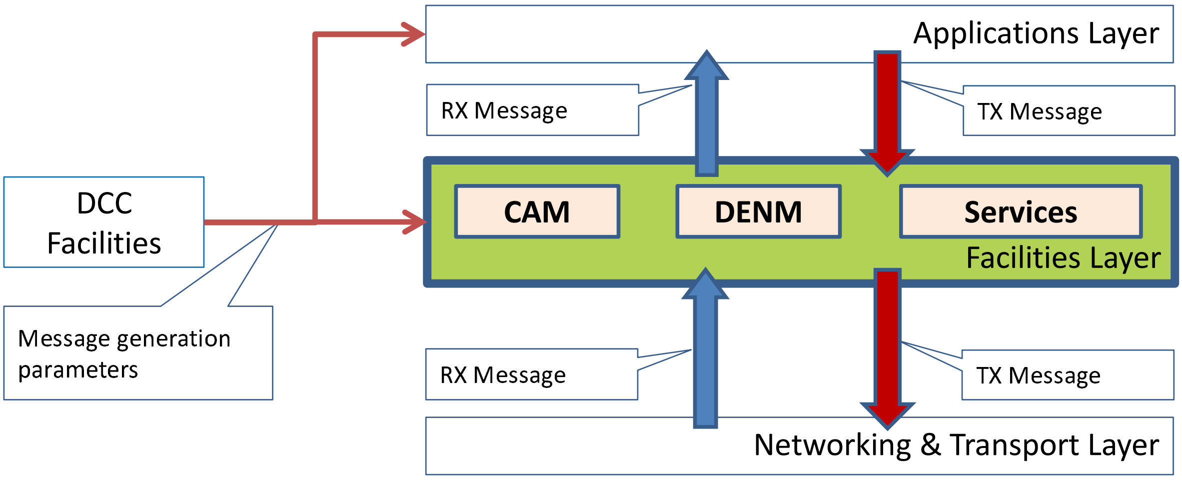

Figure 6: Facilities layer DCC interactions

Table 2: Facilities layer DCC functionality

Facilities Layer DCC functionality			
Type	**Name**	**from / to**	**Description**
Input	TX message	Application Interface	As given in ETSI EN 302 665 [i.10]. Under DCC rate control.
	RX message	Networking & Transport	As given in ETSI TS 102 723-11 [i.9] No impact from DCC.
	Message generation parameters	DCC_CROSS_Facilities	Indicate the share of radio resources the ITS-S can use.
Output	TX message	Networking & Transport	As given in ETSI TS 102 723-11 [i.9]. Under DCC rate control.
	RX message	Application Interface	As given in ETSI EN 302 665 [i.10]. No impact from DCC.

5.3.2 Networking and transport layer

The role of the networking and transport layer DCC functions (DCC_NET), depicted in Figure 7, is to provide global DCC parameters and to disseminate the local DCC parameters to other ITS-S. These DCC functions also enable multichannel operation. The networking and transport layer DCC functions are described in Table 3.

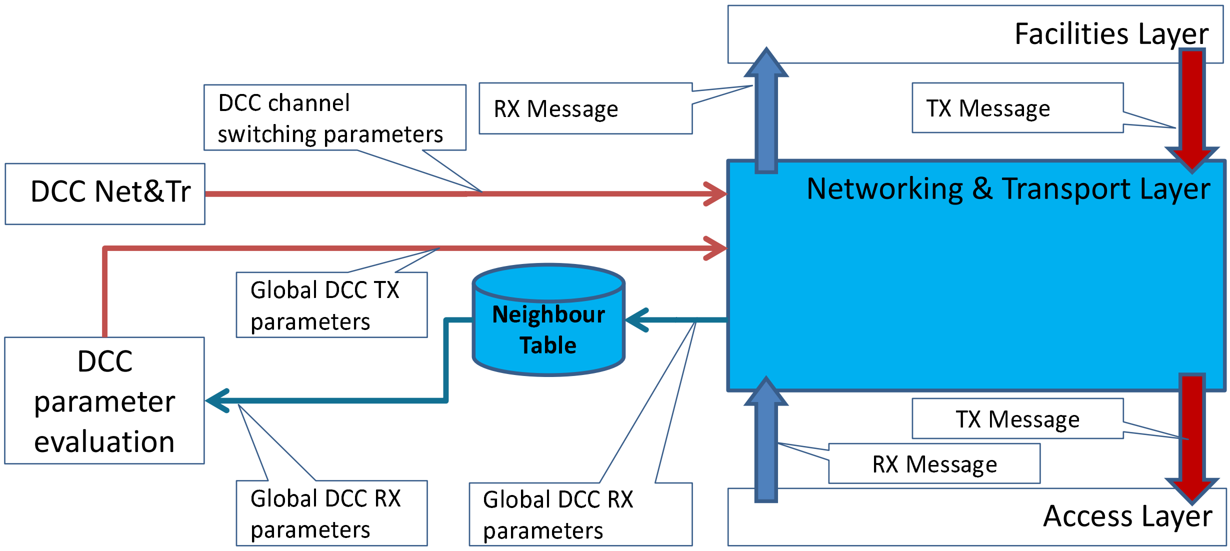

Figure 7: Networking & Transport Layer DCC interactions

Table 3: Networking & Transport Layer DCC functionality

Networking & Transport Layer DCC functionality			
Type	**Name**	**from / to**	**Description**
Input	TX message	Facilities Layer	Primitive specified in ETSI TS 102 723-11 [i.9]
	RX message	Access Layer	The global DCC RX parameters can be extracted from the GN header of the RX message from the Access Layer as given in ETSI TS 102 723-10 [i.8]
	DCC channel switching parameters	DCC_CROSS_Net&Tr	Based on the message type and the DCC channel switching parameters a message is rerouted to another radio channel as given in ETSI TS 102 723-10 [i.8]
	Global DCC TX parameters	DCC parameter evaluation	The global DCC TX parameters as specified in ETSI TS 102 636-4-2 [i.4] can be put into the GN header of the TX message handed over to the Access Layer. They are used as input to the DCC_NET as basis for controlling the CL
Output	TX message	Access Layer	Primitive specified in ETSI TS 102 723-10 [i.8]
	RX message	Facilities Layer	Primitive specified in ETSI TS 102 723-11 [i.9]
	Global DCC RX parameters	DCC parameter evaluation via Neighbour Table	The global DCC RX parameters as specified in ETSI TS 102 636-4-2 [i.4] are put into the Neighbour Table for further processing by the DCC parameter evaluation function

5.3.3 Access layer

5.3.3.1 Gatekeeper architecture

A DCC gatekeeper component (DCC_ACC) is located at the access layer. It performs traffic shaping and restricts the access to a particular channel based on the output from the DCC algorithm. An overview is shown in Figure 8 and details are given Table 4 and shown in Figure 9.

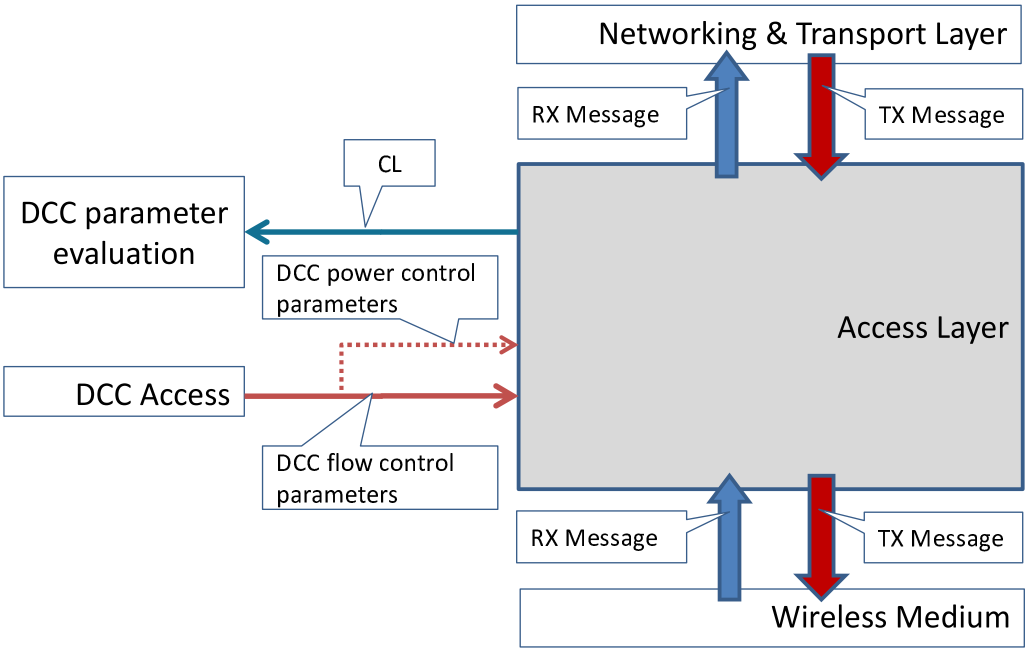

Figure 8: Access Layer DCC interactions

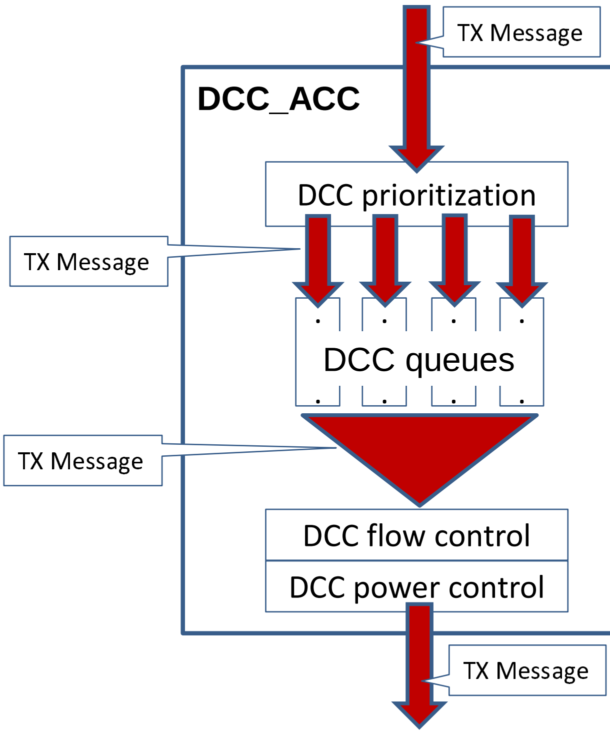

Figure 9: Gatekeeper Component DCC_ACC

Table 4: DCC Access Layer functionality

Access layer DCC functionality			
Type	**Name**	**from and to**	**Description**
Input	TX message	Networking & Transport layer	As given in ETSI TS 102 723-10 [i.8]. Under DCC rate (and power) control.
	RX message	Wireless Medium	No impact from DCC
	flow control parameters	DCC Access	Share of radio resources the ITS-S can use
Output	CL	DCC parameter evaluation	Used as input to the DCC function as basis for controlling the CL.
	TX message	Wireless Medium	Under DCC rate (and power) control
	RX message	Networking & Transport layer	As given in ETSI TS 102 723-10 [i.8]. No impact from DCC.
NOTE: The message rate is controlled by dropping packets according to their priority and life time. DCC power control should be only applied when global DCC parameter dissemination is available to align the DCC parameters between ITS-S in range.			

The Gatekeeper component DCC_ACC includes four DCC-related functions: DCC prioritization, DCC queue, DCC flow control and DCC power control. Considering traffic shaping (e.g. access restrictions) performed by the DCC flow control function, DCC queues are used to temporarily store a TX message if the channel is not available before it is passed to the medium access control layer (MAC). TX messages are enqueued by the DCC prioritization function based on the TCs associated to the TX message and dequeued by the DCC flow control function based on the highest priority first. DCC queues are used to provide a prioritized storage based on TC priorities, as well as to allow extracting stored messages, when the application-defined lifetime has expired. Finally, a given TX power level is associated to the TX message by the DCC power control function. This is illustrated in Figure 9.

The details of the DCC functions of the gatekeeper are provided in clauses 5.3.3.2 to 5.3.3.6.

5.3.3.2 Traffic class prioritization

The role of the traffic class prioritization is to select the DCC queues according to the traffic class per channel. The TC corresponding to the highest EDCA access class will be mapped to the highest priority DCC queue, so that it is dequeued by the DCC flow control first. More details are provided in Figure 10 and in Table 5.

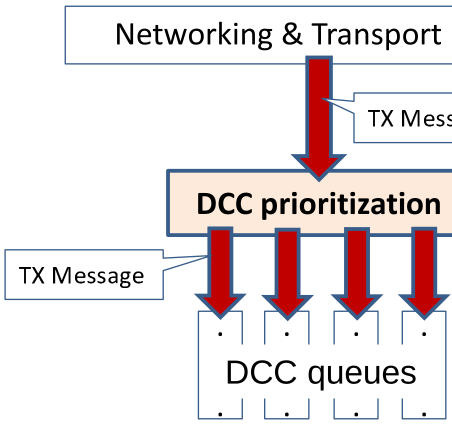

Figure 10: Traffic class prioritization function

Table 5: Traffic class prioritization functionality

Traffic class prioritization functionality			
Type	**Name**	**from and to**	**Description**
Input	TX message	Networking & Transport layer	Primitive specified in ETSI TS 102 723-10 [i.8]
	TC per TX message	Networking & Transport layer	Taken out from the header of the TX message, for example in the GN header as defined in ETSI EN 302 636-4-1 [i.3]. It identifies the transmit channel
Output	TX message	DCC queues	For each channel, the selection of the queue is done based on the traffic class that is mapped to one out of four IEEE 802.11 access categories used on the PHY interface
NOTE: Transmit channel and access categories are mapped to a TC ID included in the TX field and transmitted over the radio link.			

5.3.3.3 DCC queues

If the needed channel resources exceed the available resources messages are queued. If the queuing time of the message exceeds its lifetime, the message is dropped and an indication including the queue from which the message was removed may be given to the management entity. This information can be used to inform the facility/application about the message drop event. Details are provided in Figure 11 and in Table 6.

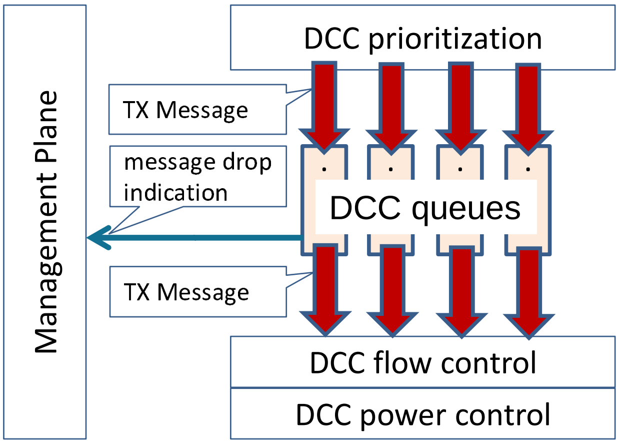

Figure 11: DCC queues

Table 6: DCC queues functionality

DCC queues functionality			
Type	**Name**	**from and to**	**Description**
Input	TX message	DCC prioritization	Tx message to be temporarily stored in case the DCC flow control blocks channel access.
Output	TX message	DCC flow control (DCC power control)	Tx message leaves the DCC queue prioritized based on TCs.
NOTE: Each queue is mapped to one out of four EDCA access categories as defined in ETSI EN 302 663 [i.11].			

5.3.3.4 DCC power control

The DCC power control function determines the output power level of the transmitter, based on the values provided by the DCC_CROSS_Access function and by the interference mitigation techniques described in ETSI TS 102 792 [i.14]. Details are provided in Figure 12 and in Table 7. Packets leaving the DCC queues according to the DCC flow control function are assigned a TX power according to either the DCC_CROSS_Access function to limit the congestion on the channel, or by the Interference mitigation function to mitigate the interferences with TTT road tolling systems.

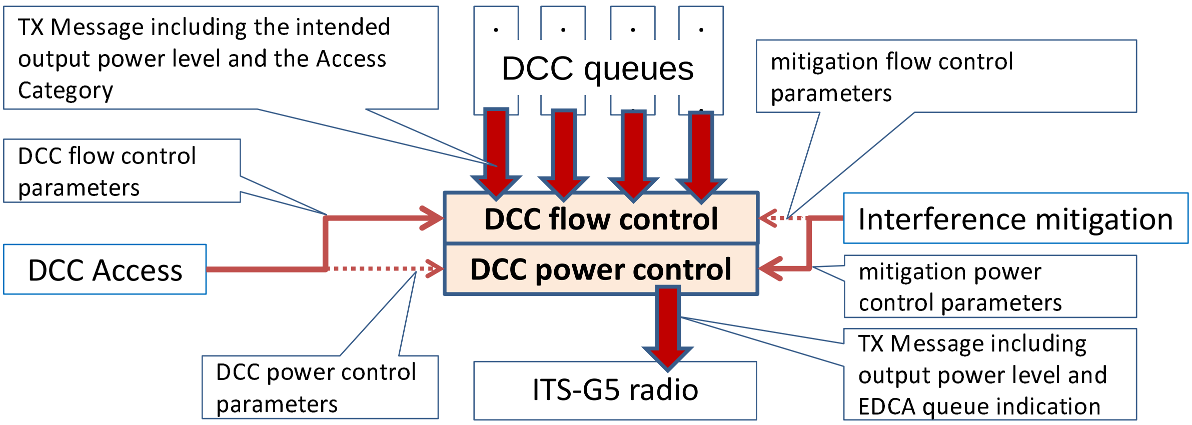

Figure 12: DCC power and flow control functions

Table 7: DCC power control functionality

DCC power control functionality			
Type	**Name**	**from and to**	**Description**
Input	TX message	DCC queues	Packet leaving a DCC queue to be assigned a TX power set by the DCC_CROSS_Access.
	Output power level	DCC queues	According to the TX power indicated in the TX message coming from the IN SAP as given in ETSI TS 102 723-10 [i.8]
	Output power level	Interference mitigation	According to ETSI TS 102 792 [i.14]
	Output power level	DCC_CROSS_Access	Restricting TX power per channel according to ETSI EN 302 571 [i.12]
	Access Category	DCC queues	Used to decide which TX power level to be used.
Output	TX message	DCC flow control	Message with assigned TX power level
	Output power level	DCC flow control	Final output power level to be used by the ITS-G5 radio.
NOTE 1: Depending on the message priority, the interference mitigation (coexistence matters) or the DCC entity might restrict the power level requested by higher layers. Details are out of scope of the present document.			
NOTE 2: Power control is a required functionality specified in spectrum regulation with a minimum control range of 30 dB, see ECC/DEC/(08)01 [i.13].			
NOTE 3: The power control should be based on discrete power steps covering at least the minimum control range.			

5.3.3.5 DCC flow control

The DCC flow control function performs data traffic shaping as specified in ETSI TS 102 687 [i.2] based on the inter frame space parameter T_{off} provided by the DCC_CROSS_Access function and the interference mitigation function respectively (ETSI TS 102 792 [i.14]). When T_{off} times out, the next message starting from the highest priority can be dequeued (i.e. the message from the DCC queue with highest priority should be taken first). After the message is handed over to the MAC, the T_{off} timer can be restarted and the procedure should be repeated until all queues are empty (The messages are also taken out from the queue when they reach the end of their lifetime, in this case the messages are deleted (dropped) and not transmitted). Details are provided in Figure 12 and in Table 8.

Table 8: DCC flow control functionality

DCC flow control functionality			
Type	**Name**	**from and to**	**Description**
Input	TX message	DCC queues	Messages extracted from the DCC queues, dequeuing from the highest priority DCC queue first, when the DCC flow control parameters allow it.
	DCC flow control parameters (T_{off})	DCC_CROSS_Access	As defined in ETSI TS 102 687 [i.2]
Output	TX message	ITS-G5 radio	Message ready to be transmitted to the wireless medium.

5.3.3.6 ITS-G5 radio

The ITS-G5 radio represents the functionalities of the IEEE 802.11-2012 as specified in [i.1], it is the interface to the ITS-G5 wireless medium. More details are provided in Figure 13 and in Table 9.

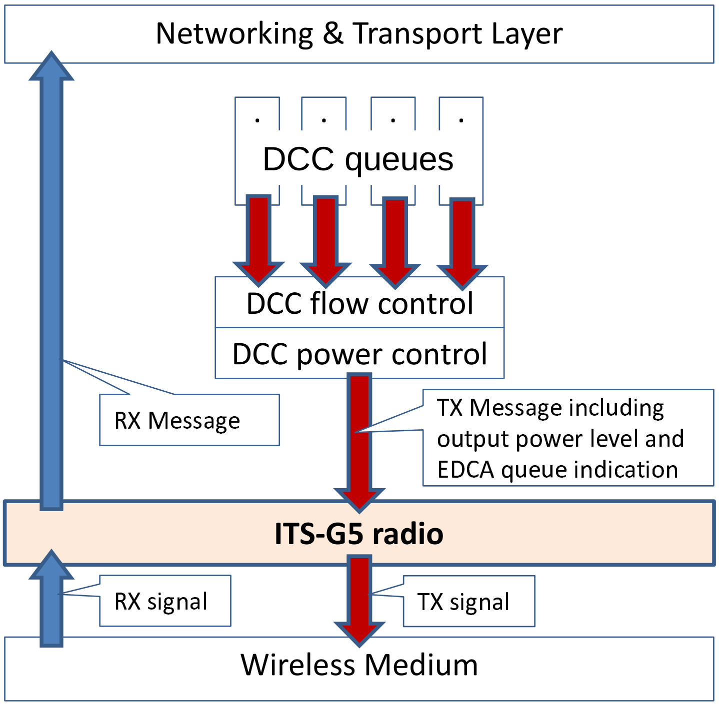

Figure 13: ITS-G5 radio

Table 9: ITS-G5 radio functionality

ITS-G5 radio functionality			
Type	**Name**	**from and to**	**Description**
Input	TX message	DCC power control	Message corresponding to the highest priority from all messages in the DCC queues
	RX signal	Wireless Medium	Message received by the ITS-G5 radio
Output	TX signal	Wireless Medium	Message transmitted to the wireless medium
	RX message	Networking & Transport layer	Primitive specified in ETSI TS 102 723-10 [i.8]

5.3.4 Management plane

5.3.4.1 DCC_CROSS component

The DCC_CROSS component is located in the management plane as shown in Figure 1. This component provides the following functions (see also Figure 5):

- DCC_CROSS_Facilities (see clause 5.3.4.2),
- DCC_CROSS_Net&Tr (see clause 5.3.4.3),
- DCC parameter evaluation (see clause 5.3.4.4),
- DCC_CROSS_Access (see clause 5.3.4.5),
- CBR evaluation (see clause 5.3.4.6).

5.3.4.2 DCC_CROSS_Facilities

The role of the DCC_CROSS_Facilities function is to indicate the availability of the radio resources to the registered applications (running various subsequent application-level services) and all required facilities services. Based on the output from the DCC parameter evaluation function and the DCC_CROSS_Net&Tr function, the DCC_CROSS_Facilities function provides as output a CR_{Limit} that can be allocated to applications and facilities. Details are provided in Figure 14 and in Table 10.

NOTE: The definition of the registered applications, resources per application or facilities services is currently in the process of being specified by the ETSI TC ITS WG1.

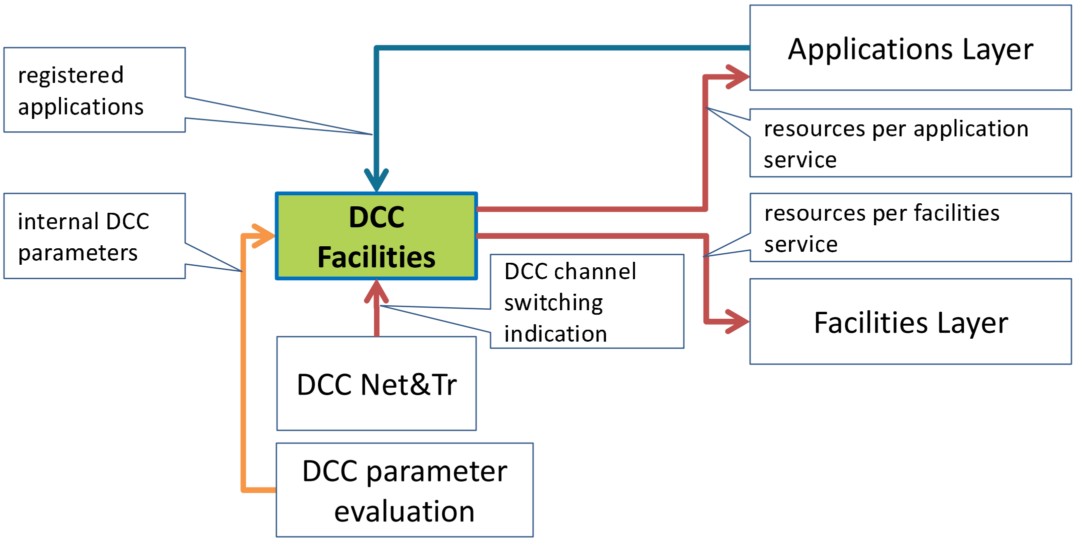

Figure 14: DCC_CROSS_Facilities function

Table 10: DCC_CROSS_Facilities functionality

DCC_CROSS_Facilities functionality			
Type	**Name**	**from and to**	**Description**
Input	registered applications	Applications	Based on FA interface.
	internal DCC parameters	DCC parameter evaluation	The currently available channel resource limit CR_{Limit} provided by DCC parameter evaluation function.
	DCC channel switching indication	DCC_CROSS_Net&Tr	Considering multi-channel operations, some channels might not be available because the transceiver is tuned to a different frequency band.
Output	resources per facility service	Facilities	Provides the available channel resources.
	resources per application service	Applications	Provides the available channel resources.
NOTE: The resource allocation process is not specified yet.			

5.3.4.3 DCC_CROSS_Net&Tr

The role of the DCC_CROSS_Net&Tr is to provide DCC parameters measured by neighbouring ITS-S to the DCC parameter evaluation function. Additionally, the DCC_CROSS_Net&Tr influences data offloading to other radio channels based on the internal DCC parameters. More details are provided in Figure 15 and in Table 11.

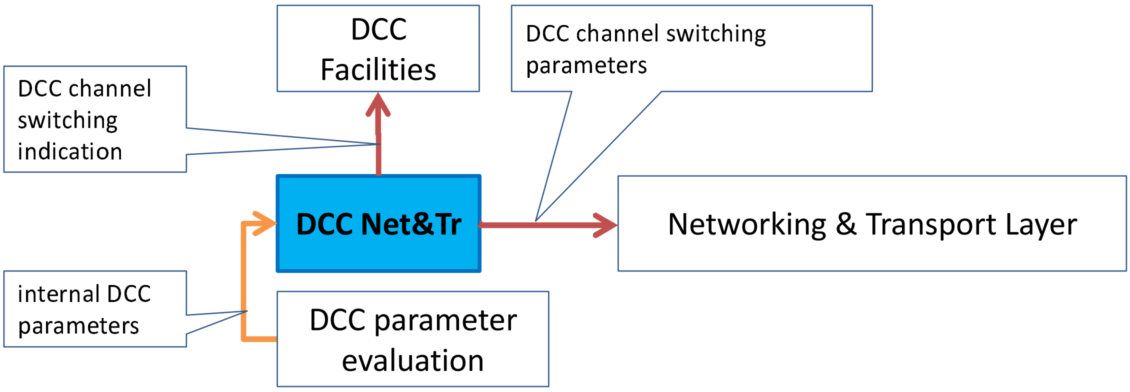

Figure 15: DCC_CROSS_Net&Tr function

Table 11: DCC_CROSS_Net&Tr functionality

DCC_CROSS_Net&Tr functionality			
Type	**Name**	**from and to**	**Description**
Input	internal DCC parameters	DCC parameter evaluation	CL percentage per channel.
Output	DCC channel switching indication	DCC_CROSS_Facilities	Indicates to the DCC_CROSS_Facilities function that a packet has been switched to a different channel
	DCC channel switching parameters	Networking & Transport	Indicates other channels to which a message may be rerouted.
NOTE: Details are described in ETSI TS 102 636-4-2 [i.4].			

5.3.4.4 DCC parameter evaluation

The DCC parameter evaluation function determines the channel resources available for one ITS-S based on local and global DCC parameters. It provides this information subsequently to all DCC_CROSS functions and it also provides global DCC TX parameters to be disseminated to neighbouring ITS-S. More details are provided in Figure 16 and in Table 12.

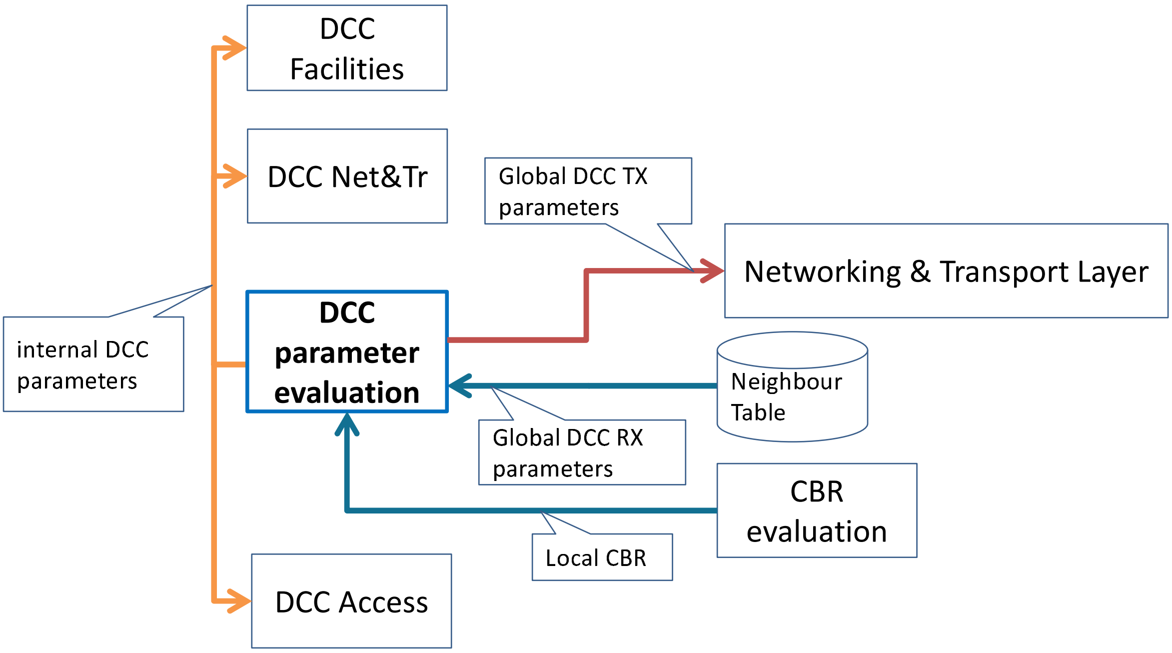

Figure 16: DCC parameter evaluation function

Table 12: Functionality of DCC parameter evaluation

Functionality of DCC parameter evaluation			
Type	**Name**	**from and to**	**Description**
Input	local CBR	CBR evaluation	Local measurement of the CBR obtained by the CBR evaluation function.
	global DCC RX parameters	Neighbour Table	Global evaluation of the CBR provided by each neighbour and stored in the neighbour table.
Output	internal DCC parameters	DCC_CROSS_Facilities, DCC_CROSS_Net&Tr, DCC_CROSS_Access	Available CL percentage per channel.
	Global DCC TX parameters	Networking & Transport	DCC TX parameters, such as CBR or TX power level.
NOTE: The DCC parameter evaluation block represents the main DCC control entity. It allocates the channel resources.			

5.3.4.5 DCC_CROSS_Access

The DCC_CROSS_Access function determines the message rate limit. It takes the internal DCC parameters as well as the length of the message as input and adjusts the flow control parameter T_{off}. Optionally, it can also reduce the TX power level to shorten the radio range in road traffic scenarios with very high vehicle densities. More details are provided in Figure 17 and in Table 13.

T_{off} per channel is calculated from the length T_{on} (air time) of the last transmitted message and the CL percentage per channel. $T_{off} = T_{on} \times ((1 - u_t) / u_t)$, where u_t is the allowed channel utilization per ITS-S (available CL percentage) obtained from the DCC algorithm.

T_{off} is not used for the highest priority queue. Accordingly, a separate rule is necessary to avoid a constant flow of high priority messages, which would break the DCC flow control. The DCC_CROSS_Facilities function provides a parameter specifying the maximum number of multiple transmissions of such high priority message (e.g. 5 consecutive messages). The extra transmissions will be taken into account by the CBR measurement and DCC will adapt to the temporary increased CBR.

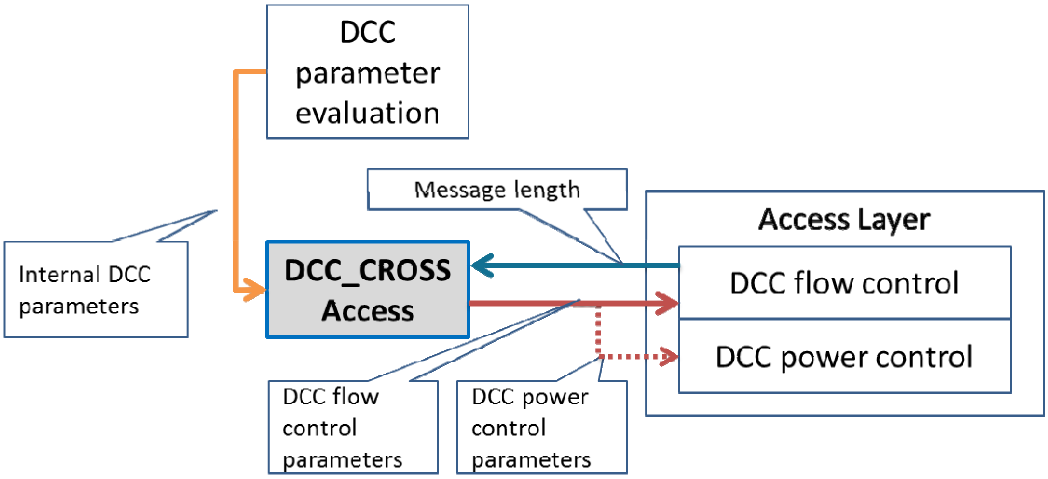

Figure 17: DCC_CROSS_Access function

Table 13: DCC_CROSS_Access functionality

DCC_CROSS_Access functionality			
Type	**Name**	**from and to**	**Description**
Input	internal DCC parameters	DCC parameter evaluation	Available CL percentage per channel.
	message length (time T_{on})	DCC flow control	Message length used in conjunction with the data rate to extract the message air time T_{on}.
Output	DCC flow control parameter T_{off}	DCC flow control	Flow control parameter (T_{off}) provided as function of the internal DCC parameters.
	DCC power control parameters (optional)	DCC power control (optional)	TX power level provided as function of the internal DCC parameters.

5.3.4.6 CBR evaluation

The CBR evaluation function is in charge of pre-processing the CL measurement obtained by the radio and to harmonize the CL values obtained from different chipsets. The output of this function is a local measurement of the CBR according to ETSI TS 102 687 [i.2]. More details are provided in Figure 18 and in Table 14.

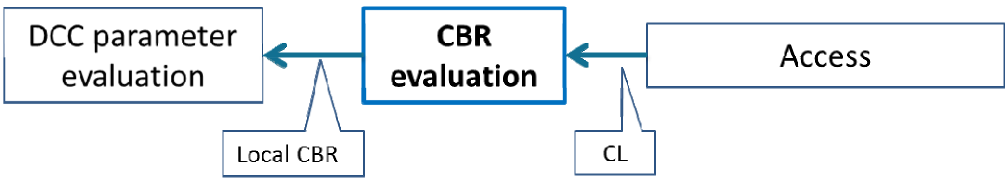

Figure 18: CBR evaluation function

Table 14: Functionality of CBR evaluation

Functionality of CBR evaluation			
Type	**Name**	**from and to**	**Description**
Input	channel load (CL)	Access Layer	CL measurement according to IEEE 802.11-2012 [i.1].
Output	local CBR	DCC parameter evaluation	Pre-processed CL percentage per channel
NOTE: The radio chipset does a measurement of the CL. The CBR evaluation function adapts the CBR results for various CL measurement implementations.			

5.4 Channel load limits

5.4.1 Basic system level assumptions

The present document does not aim at specifying a specific DCC algorithm, but rather designs guidelines to be fulfilled by any DCC algorithm to allocate channel resources efficiently and fairly to each ITS-S.

From a system level point of view the objective of DCC is to allow as many ITS-S as possible to reliably exchange messages with each other. This includes the provision of reserved resources for high priority messages and the reduction of harmful influence of packet collisions caused by hidden nodes.

The objective of the DCC mechanisms is also to satisfy fairness as defined in clause 3.1.

These assumptions imply that all ITS-Ss are acting according to some common rules that can be easily tested.

In clause 5.4.2, a simple test procedure is suggested. Based on this procedure, a system level CBR limit is proposed in clause 5.4.3. From the system level view limits, test limits for each ITS-S are evaluated in clause 5.4.4.

5.4.2 Test procedure concept

The behaviour of a DCC implementation can be tested by a RF black-box test procedure. An ITS-S implementing a typical DCC algorithm is subject to a given CL and reacts by adjusting its TX parameters. In such test, the appropriate CL is reproduced by one or multiple ITS-S sending modulated RF signals (emulating data packets) at a TX rate required to reach the aimed CL. For initial implementations based on a local CBR measurement, the emulated CL should consist of correctly coded ITS-G5 data packets with different power levels at the ITS-G5 receiver under test. The test signal (RX) should be independent of the device under test (DUT) transmission (no collision avoidance on the signal generator side). It can be fed to the DUT over a RF circulator to decouple the test signal generator from the DUT (see Figure 19). The DUT transmission can be decoupled by the same circulator to a power detector. The detector output (TX) can be sampled with 1 bit resolution. The power threshold for the 1 bit quantization should be adjusted in such a way that the strong DUT transmission can be discriminated from the weak test signal. The time resolution should be chosen in such a way, that the ITS-G5 transmit interval can be measured with 2 % relative accuracy. The DUT should be configured in such a way that for an empty channel it transmits packets of equal size at full rate (approximately 10 Hz). The packet size can be determined in an independent measurement. The relative accuracy of this measurement should be 2 %.

The same test setup can be used to assess the correct handling of DCC information sharing when applicable to the DUT. In this case (Figure 20) the generated test signal should also include correctly coded DCC header information (e.g. as part of the GN extended header). This more advanced configuration can also be used for DUTs that are not capable to decode the DCC header. In this case only the RSSI statistics of the signal are of relevance for the test result.

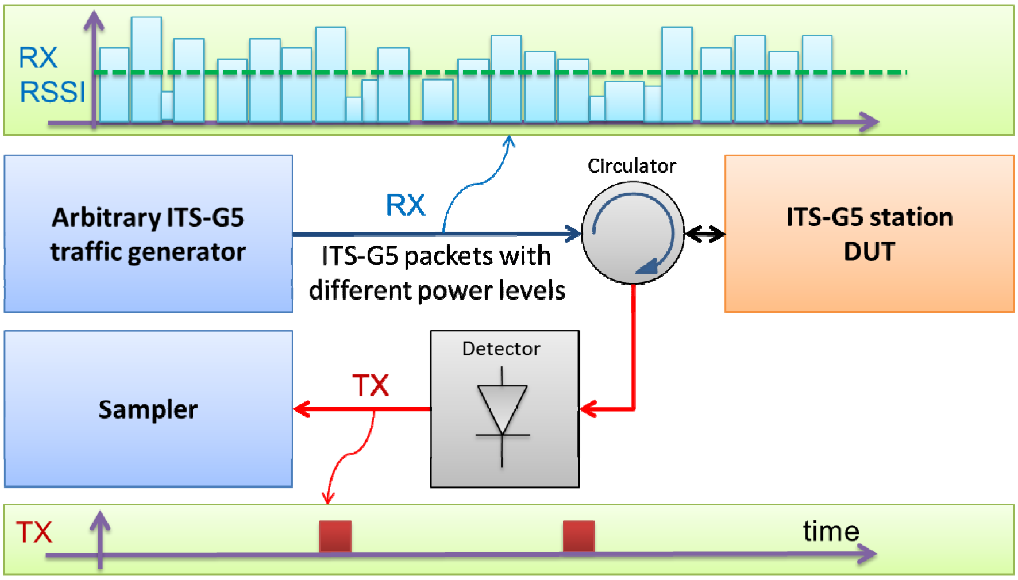

Figure 19: Test of local CBR measurement

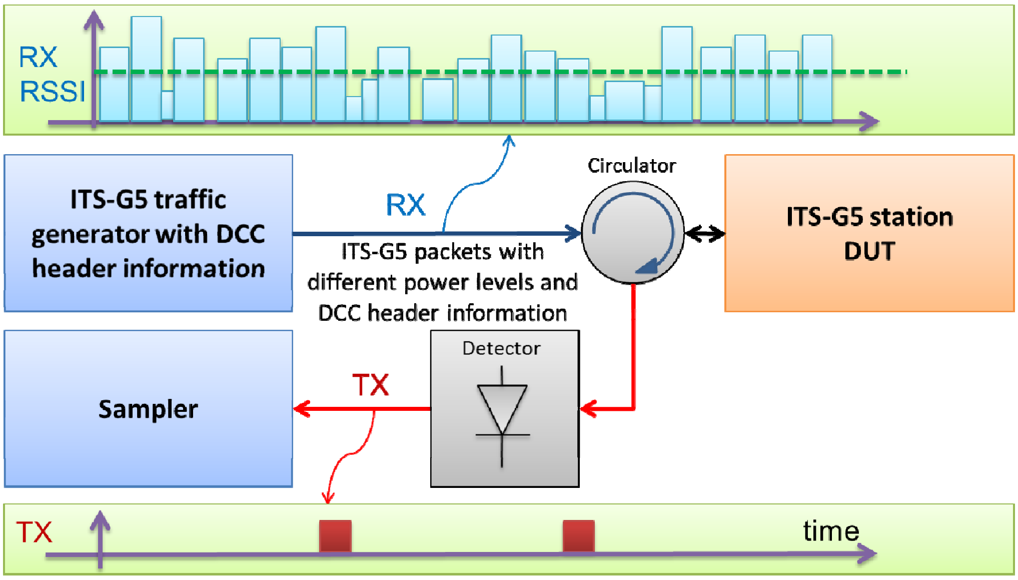

Figure 20: Test of DCC information sharing (can also be used for local CBR measurement)

5.4.3 System level CBR limit for conformance test

The ITS-G5 radio channel provides a maximum load capacity. When the CL comes close to this limit, the number of packet collisions increases and, when even more packets are put on the channel, the CL value saturates. The number of successfully received packets decreases in this overload situation. A CL of more than 85 % is critical for an ITS-G5 system, but to leave headroom for safety critical messages the normal data traffic should not load the channel by more than 75 %. In the following text the CL will be described by the CBR value which is the outcome of a specific measurement procedure.

The local CBR value is evaluated from the actual local CL to estimate the system wide channel usage. This estimation can be enhanced by dissemination of this local CBR value between the ITS-S in radio range (global CBR).

For an individual ITS-S the following parameters influence the local CL measurement result:

- Number of ITS-S (N_{Sta}) in reception and in carrier sense range
- Radio environment (defines the ranges)

- Road traffic scenario (vehicle densities in reception and in carrier sense range)
- Message duration (T_{on})
- Message rate (R_M) or idle time (T_{off})
- Transmit power level (P_{TX}) (defines the ranges)

The radio environment given by the road traffic scenario is an external parameter that cannot be controlled. But, since the radio environment determines the number of ITS-S N_{Sta} contributing to the CBR, N_{Sta} sufficiently describes the relevant network properties from a DCC system point of view.

An individual ITS-S can vary the message rate or idle time and the transmit power level to control its own contribution to the total channel utilization.

Under the fairness assumption that all ITS-Ss contributing to the CBR should share the available resources for periodic messages, an individual upper limit of the channel utilization should be respected by each ITS-S. This individual upper limit may be calculated by dividing the total available channel capacity by the total number of ITS-Ss (see equation 4).

NOTE 1: As each ITS-S may use the channel up to such limit, excess capacity may be consumed by other ITS-S without violating the system channel capacity limit. The channel capacity balancing is done implicitly or even explicitly by implementation specific DCC algorithms.

A test system as described in clause 5.4.2 could test whether an implementation is conformant to such a limit when it simulates the CL that a certain number of ITS-S would produce when they all are contributing to the CL according to their individual channel utilization limits.

In an implementation, each ITS-S should find its individual channel utilization limit from the information available to it. From a system level point of view this could be done as described above by dividing the total available channel capacity by the total number of ITS-Ss. Assuming that the total channel capacity is known, only the number of ITS-Ss N_{Sta} contributing to the CL is to be found.

There are different ways to estimate the number of ITS-Ss used by a DCC algorithm. In the present document, the following approaches are taken into consideration:

- Count the number of entries in the network layer location table (specified in ETSI EN 302 636-4-1 [i.3]) (explicit use of N_{Sta}). The disadvantage of this approach is that outdated or missing entries in the location table influence the DCC behaviour.

- In a standard can be specified that for each number of neighbours N_{Sta} the CBR value is not allowed to exceed a limit that is defined by a function of the N_{Sta} value. Or in other words, the CBR limit can be defined to be a specified function of N_{Sta}. Hence, the individual channel utilization can be evaluated directly from the measured CBR value without the explicit knowledge of N_{Sta}. Most proposed DCC algorithms follow this approach of taking the CBR value as input to directly calculate the individual channel utilization limit. The disadvantage of this approach is that uncertainties of the CBR measurement influence the DCC behaviour. The stronger the dependency of the CBR limit on the N_{Sta} value, the more robust the DCC algorithm is against measurement uncertainties.

For a test system, as described in clause 5.4.2, the relation between CBR and N_{Sta} should be as simple as possible to make a straight forward test procedure possible. Most DCC algorithms define this relation only implicitly. This results in hyperbolic, root, or exponential functions for CBR in N_{Sta}. The present document proposes to use a linear function for the CBR limit, as shown in equation 1.

$$CBR_{Limit} = N_{Sta} \times a + b \quad CBR_{Limit} = N_{Sta} \times a + b \qquad (1)$$

CBR_{Limit} is the maximum portion of the global channel resource that can be used by all ITS-Ss in radio range of each other. The parameters a and b are chosen to support different scenarios. The choice of parameter b is driven by typical small crossing city traffic scenarios, where a low value of N_{Sta} but a lot of ITS-S are hidden in non-line-of-sight conditions. The parameter a is chosen by the maximum possible CBR as supported by the access layer in relation to the maximum number of supported ITS-Ss. A higher value of a reduces the sensitivity of the DCC control loop on inaccuracies of the CBR measurement, but it lowers the maximum number of supported ITS-Ss due to channel overload.

The outcome of equation 1 for following parameter values common to all ITS-S is depicted in Figure 21:

$$a = 0{,}000375 \qquad (2)$$

$$b = 0{,}5 \qquad (3)$$

From the CBR_{Limit} and the fairness assumption for periodic messages, the channel utilization limit CR_{Limit} can be calculated. It represents the maximum channel resources available for each ITS-S contributing to the CBR.

$$CR_{Limit} = \frac{CBR_{Limit}}{N_{Sta}} \; CR_{Limit} = \frac{CBR_{Limit}}{N_{Sta}} \qquad (4)$$

A test system can emulate an ITS-G5 signal with a virtual ITS-S number of N_{Sta}, resulting in a CBR value of CBR_{Limit}, as stimulus to check whether a certain implementation is not exceeding the CR_{Limit} that corresponds to the same virtual N_{Sta} value.

NOTE 2: The DUT usually will not be aware of the simulated number of ITS-S. It just reacts to the CBR measured at the receiver.

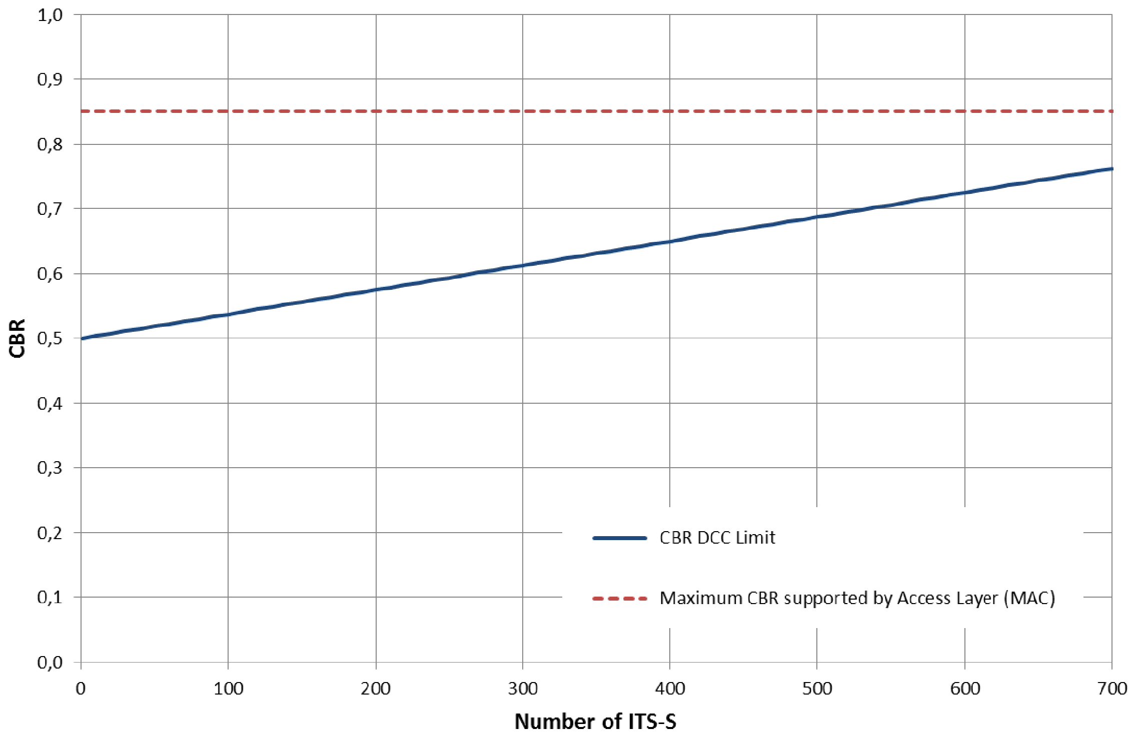

Figure 21: CBR limit in function of number of ITS-S that can be used as conformance test limit

5.4.4 Channel load limits for each individual ITS-S

The channel resource CR_{Sta} utilized by an ITS-S is given by the transmit time T_{on} (message duration) and the idle time T_{off} where the ITS-S is not transmitting.

$$CR_{Sta} = \frac{T_{on}}{T_{on} + T_{off}} \; CR_{Sta} = \frac{T_{on}}{T_{on} + T_{off}} \qquad (5)$$

For a given message duration T_{on} the message rate limit R_{Limit} and thereby the idle time limit $T_{offLimit}$ before accepting the next message can be evaluated from the channel resource limit CR_{Limit}.

$$R_{Limit} = \frac{CR_{Limit}}{T_{on}} \; R_{Limit} = \frac{CR_{Limit}}{T_{on}} \qquad (6)$$

$$T_{off\ Limit} = T_{on} \times \left(\frac{1 - CR_{Limit}}{CR_{Limit}} \right) \quad (7)$$

Figure 22 shows the upper message rate limit R_{Limit} for a message duration T_{on} of typical 0,6 ms and for a maximum message duration of 1 ms, when the CBR_{Limit} is used according to equations 1, 2 and 3 and the rate limit R_{Limit} is calculated with equation 6.

The idle time limit $T_{offLimit}$, calculated with equation 7, is used by the DCC flow control mechanism to reset the T_{off} counter to its initial value, as described in clause 5.3.3.5. Figure 23 depicts the results from equation 7 for the parameters *a* and *b* given in equation 2 and equation 3.

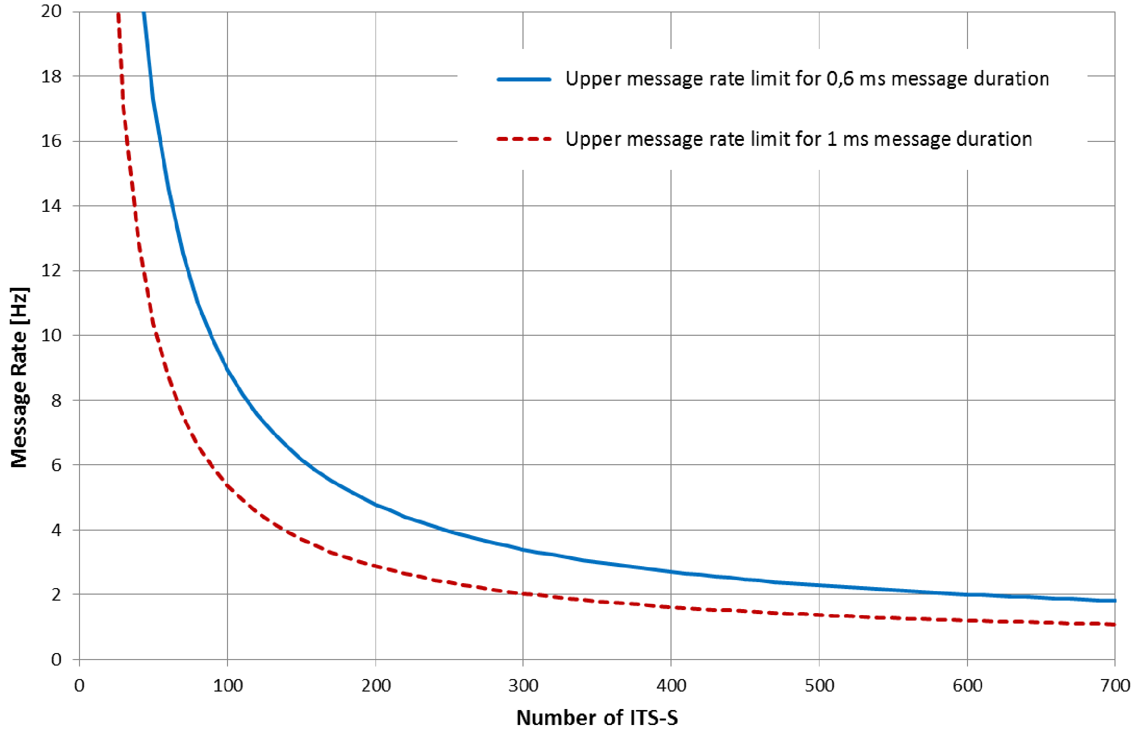

Figure 22: Upper message rate limit resulting from the CBR DCC limit shown in Figure 21 for a message duration of 0,6 ms and 1 ms

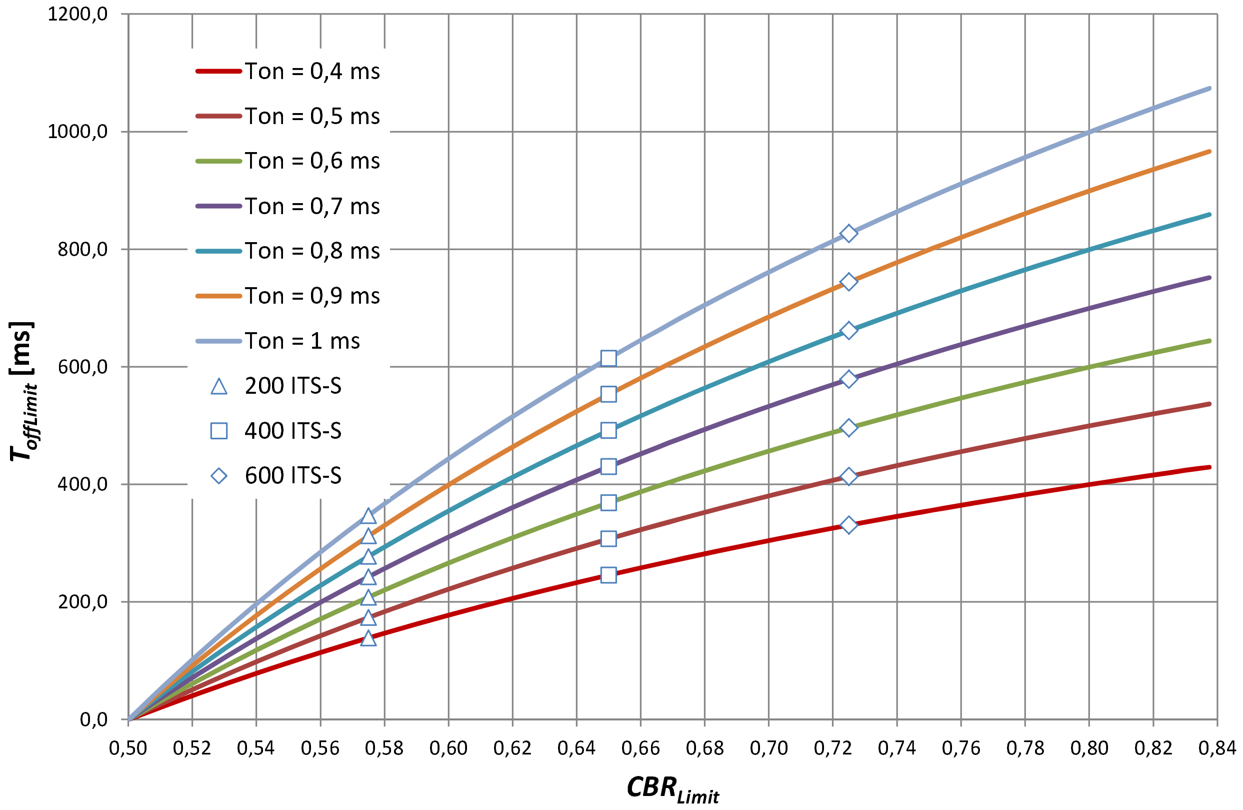

Figure 23: Minimum idle time limit $T_{offLimit}$ as function of the message length T_{on} and the CBR DCC limit CBR_{Limit} as shown in Figure 21

6 Evaluation metrics

6.1 Introduction

Standardized evaluation metrics are critical for a fair and comparable evaluation of the performance of a system. The performance of DCC algorithms for ITS-S using ITS-G5 may be evaluated with communication, networking or application-level metrics. Most of the metrics are transmitter-centric and represents the impact of the DCC algorithms on the transmitter's capabilities to use the wireless channel. The IRT is a receiver-centric metrics and represents the impact of DCC algorithms on the receivers' capability to receive messages.

CL, CBR as well as RSSI/RCPI represent communication performance of the DCC algorithms. The CR or neighbour density represents network-level performance of the DCC algorithms. Finally, the IRT, a receiver-centric metric, represents application-level performance of the DCC algorithms.

6.2 Metrics measurement

The previously described metrics may be measured according to the methodology described in Table 15.

Table 15: Metric Measurement Methodology

Metric	Measurement Methodology
Channel Load (CL) [8-bit value] (a.k.a Channel Busy Ratio (CBR)) (from IEEE 802.11-2012 [i.1])	$CL_k = INT\left(\left(\frac{CBT}{(MW)\times 1024}\right)\times 255\right)$ where: $CBT = \sum_{MW} BUSY\begin{cases} PHY\ CS \\ Virtual\ CS \end{cases}$, $BUSY = 1, when\ Energy^{Ch} \geq CS^{th}$, $CS^{Th}_{Def} = -85\ dBm$ $MW = Measurement\ Window$; $MW_{Def} = 100\ ms$
Received Channel Power Indicator (RCPI) - [8-bit value] (from IEEE 802.11-2012 [i.1] - OFDM)	$RCPI_{DB} = 0\ for\ Pwr^{RX} \leq -110\ dBm$ $RCPI = INT\{(Pwr^{RX}\ in\ dBm + 110)\times 2\}$ $for\ 0\ dBm > Pwr^{RX} > -110\ dBM$ $RCPI = 220\ for\ Pwr^{RX} \geq 0\ dBM$ where: $Pwr^{RX} is\ the\ RX\ RF\ power\ within\ \pm 5dB\ accuracy\ (95\ \%\ conf.interval)$
Average RCPI ($\widehat{RCPI}$) [8-bit value]	$\widehat{RCPI} = \frac{\sum_{i=0}^{\#Frame} RCPI_i}{\#\ Frame}\ for\ \#Frame \leq 32$ $\widehat{RCPI} = \frac{\widehat{RCPI}_{t-32}\times 31}{32} + \frac{RCPI}{32}\ for\ \#Frame > 32$
Received Signal-to-Noise Indicator (RSNI) - [8-bit value] (from IEEE 802.11-2012 [i.1] - OFDM)	$RSNI_{DB} = \left(10\times log_{10}\left(\frac{(RCPI_{power} - ANPI_{power})}{ANPI_{power}}\right) + 10\right)\times 2$ where: ANPI (average noise power indicator) is a medium access control (MAC) indication of the average noise plus interference power measured when the channel is idle as defined by three simultaneous conditions: 1) the Virtual Carrier Sense (CS) mechanism indicates idle channel, 2) the station (STA) is not transmitting a frame and 3) the STA is not receiving a frame. and where $RCPI_{power}\ and\ ANPI_{power}$ are power domain values of the RCPI and ANPI; $RSNI_{DB}$ is in 0,5 dB steps from -10 dBm to 117 dBm.
Average RSNI ($\widehat{RSNI}$) [8-bit value] (from IEEE 802.11-2012 [i.1])	$\widehat{RSNI} = \frac{\sum_{i=0}^{\#Frame} RNSI_i}{\#\ Frame}\ for\ \#Frame \leq 32$ $\widehat{RNSI} = \frac{\widehat{RSNI}_{t-32}\times 31}{32} + \frac{RNSI}{32}\ for\ \#Frame > 32$
Average Noise Power Indicator (ANPI), aka Idle Power Indicator Density (IPI_Density) [8-bit value] (from IEEE 802.11-2012 [i.1])	$ANPI_k =$ $INT\left(255\times\left(\frac{IPI}{((1024\times MW) - T^{BUSY} - T^{RX} - T^{TX})}\right)\right)$ where: $IPI = Energy^{Ch}, when\ IDLE\begin{cases} PHY\ CS \\ Virtual\ CS \end{cases}$, $IDLE = 1, when\ Energy^{Ch} < CS^{th}$, $CS^{Th}_{Def} = -85\ dBm$

Metric	Measurement Methodology
Inter-Reception Time (IRT)	IRT_k: *Time interval between two successive received CAM from node k.*
Communication Range (CR)	$AR_k = MAX_i\{ED_{\overline{ki}}\},$ $where\ i \in LT_k\ and\ IRT_i \leq 1\ s$ where LT_k is the Location Table of node k and where: $ED_{\overline{ki}}$: Euclidian Distance between nodes and k and i
Neighbor Density	$AD_k = \sum_{i \in LT_k} 1_i^{AR}, where\ 1_i^{AR} = \begin{cases} 1\ if\ i \in AR_k \\ 0\ otherwise \end{cases}$ where: LT_k is the location table of *k*

7 Simulation scenarios & parameters

7.1 Scenarios definition

The present clause describes the link between input parameters, mobility scenarios, DCC algorithms and output metrics.

The aim of the present clause is to provide high level description of the objectives of the simulation evaluations. The scenarios are classified in four categories, each aiming at evaluating one testing objective. The description of the scenarios in each four category is given in Table 16.

Table 16: Scenario Descriptions

Category	Testing Objectives	Conditions	Scenarios	Mobility
1	Scalability	Homogeneous ITS-S density	1-D highway	Static
			2D Parking Lot	
2	Adaptability	Heterogeneous ITS-S density	Highway, One direction dense, one empty	Exponential Inter-distance (low on direct flow, high on contra-flow)
			Elevated Highway	Exponential Inter-distance (low on elevated highway, high on highway)
3	Resilience	NLOS	Blind Intersection	One vehicle arriving at constant speed at each corner
			Dense Blind Intersection	The East/West direction: platoon of dense static vehicles. On West/East and North/South, two vehicles approach at constant speed.
4	Responsiveness	Variable Traffic	Cluster/Platoon on one direction, single vehicle on the opposite direction	Platoons of dense vehicles, sparse conditions in-between

Since a DCC penetration rate of 100 % is not expected at Day 1, gradual penetration (10 %, 50 %) of ITS-S is also considered, first for 4-wheels motor-vehicles and also for vulnerable traffic users. The penetration rates to be considered for each type of ITS-S are given in Table 17.

Table 17: ITS-S penetration rate

ITS-S	Description	Penetration
C2X	4-wheels vehicles equipped with ITS-G5 technology	10 %, 50 %, 100 %
Smartphones	Non C2X 4-wheels vehicles equipped with Smart-Phones	10 %, 50 %, 100 %
Smartphones-Vulnerable	Vulnerable Users equipped with Smart Phones	10 %, 50 %, 100 %

Finally, channel and propagation models are critical to the evaluation. The channel models described in ETSI TS 103 257 [i.15] are used for the evaluation of the DCC algorithms presented in the present document.

7.2 Estimation of the number of ITS-S in the communication range

Figures 24 and 25 present the number of ITS-S in communication range for highway scenarios with deterministic vehicle spacing according to their speed when all vehicles are equipped with ITS-G5 transmitters. As parameters, speed, lanes and communication range are used. This figure is used for the estimation of the system-level CBR limits, as described in clause 5.4.3.

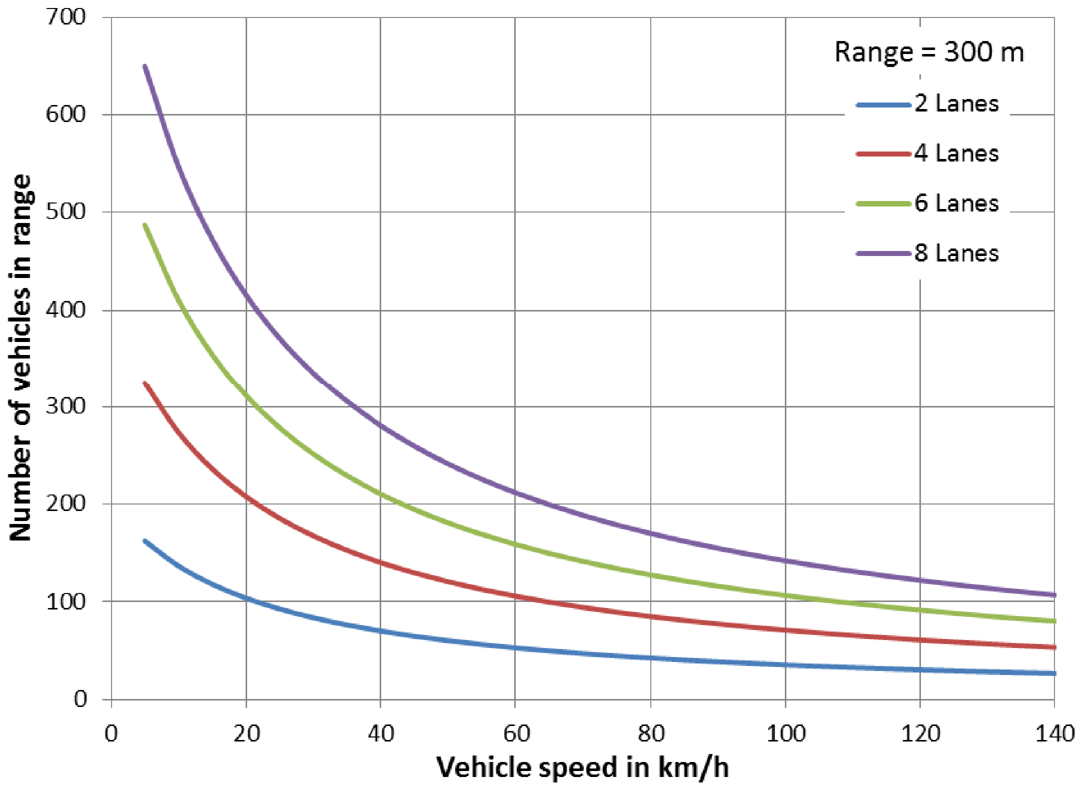

Figure 24: Possible number of ITS-S in communication range for a radio range of 300 m

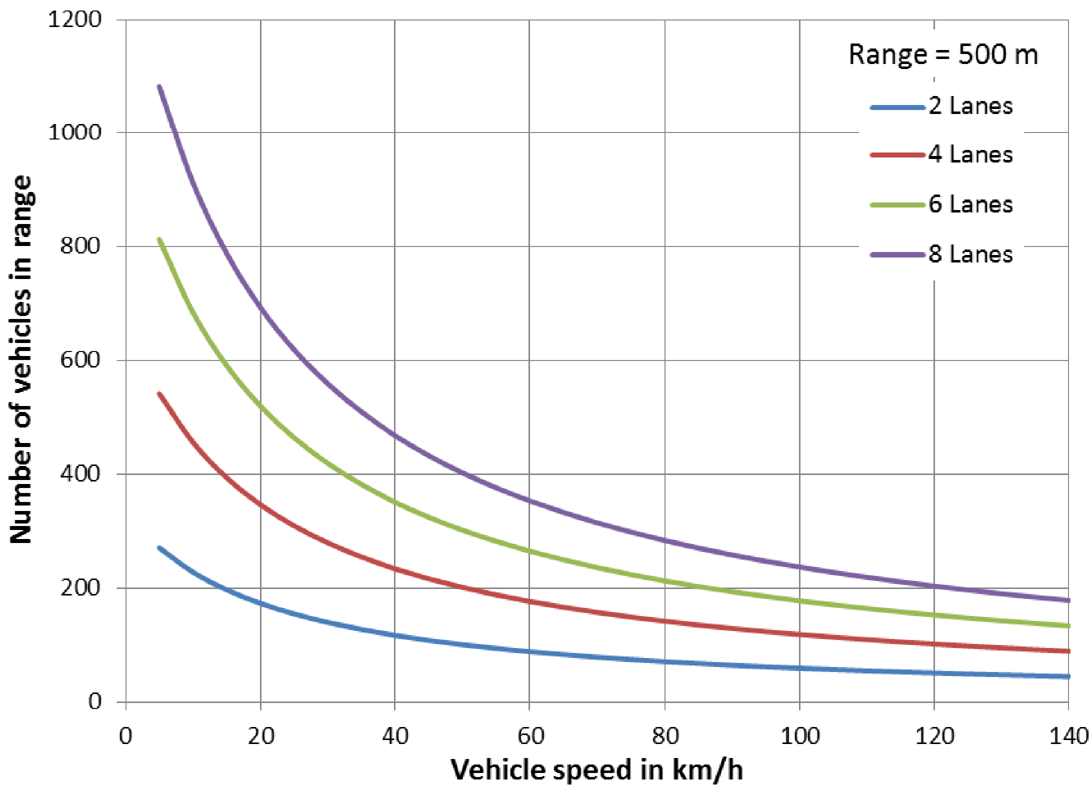

Figure 25: Theoretical number of ITS-S in range for a radio range of 500 m

7.3 Mobility scenarios

7.3.1 Homogeneous ITS-S density

7.3.1.1 General

As illustrated in Table 16, the objective of this first category of scenario is to evaluate the scalability of DCC algorithms. The described scenarios are therefore very dense and, to simplify the simulation design, all vehicles are assumed to be static. In this category of scenario, vehicular mobility, conditioned by a homogeneous distribution, does not impact any DCC algorithm.

Scalability requires a high density of vehicles, but not particularly a particular topology. In order to remain simulator agnostic, a generic scenario for scalability evaluations is specified on Table 18 regardless of specific topology. It only corresponds to an average vehicular density in three classes: *sparse, medium, dense*. A vehicle size is assumed to be 2 m × 5 m.

When specific topologies are required, a 1D Highway and a 2D Parking Lot are provided. The difference between 1D highway and 2D parking lot is the 2-dimentional exponential increase of the influence of ITS-S on the wireless channel, but even a 1D highway scenario also includes multiple lanes and directions.

Table 18: Scenario Parameter for Scalability Test

Class	Vehicular Density	Corresponding 1D parameters	Corresponding 2D parameters
Sparse	50 vehicle/km^2	100 m inter-distance / 3 lanes / 2 directions	1,5 m inter-distance, 2D
Medium	100 vehicles/km^2	45 m inter-distance / 3 lanes / 2 directions	0 m inter-distance, 2D
Dense	250 vehicles/km^2	20 m inter-distance / 3 lanes / 2 directions	-
Extreme	400 vehicles/km^2	10 m inter-distance / 3 lanes / 2 directions	-

7.3.1.2 1D highway

This scenario represents a typical highway, with 2 directions and 3 lanes in each direction. Even though the average vehicular density should be kept as in Table 18, there are also extra RSUs (ITS-S), which are located on the middle lane and are used to extract statistic (CL, IRT, P^{tx}) in constant and static locations. These RSU never transmit and, therefore, do not participate to the congestion level. The 1D highway scenario is illustrated in Figure 26 and the specific parameters are listed on Table 19.

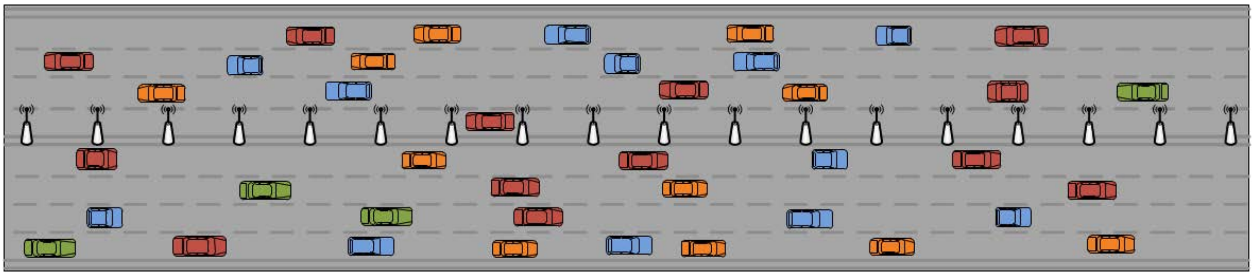

Figure 26: Illustration of a dense highway scenario, where the measuring RSUs are uniformly distributed every 100 m in the middle lane

Table 19: Specific highway configurations for scalability tests

Parameter	Value	Default
Highway Length	1 000 m to 50 000 m	10 000 m (1 000 m if static)
RSU Inter-Location	50 m to 500 m	100 m
Vehicle size	2 m × 5 m	2 m × 5 m
Flow density class	Sparse/Medium/Dense	Dense
Contra-flow density class	As Flow	Dense

7.3.1.3 2D Parking lot

In this scenario, vehicles are homogeneously distributed in a 2D space. Accordingly, this scenario uses a homogeneous 2D vehicular density as indicated in Table 18 and is adapted to fit any 2D simulation area.

7.3.2 Heterogeneous scenarios

7.3.2.1 Heterogeneous highway

In this scenario, the same *average* density classes as indicated in Table 18 are kept as much as possible. But as vehicles move, a limited heterogeneity in the local vehicular density may be observed. It corresponds to a real highway environment and is illustrated in Figure 27, where the specific configuration parameters are listed in Table 20.

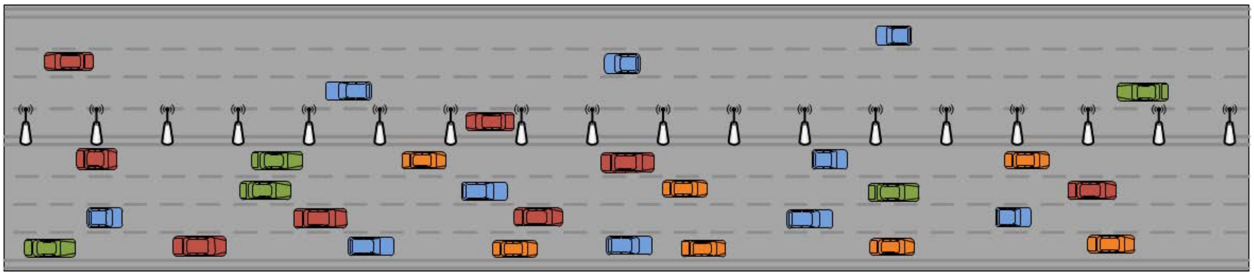

Figure 27: Heterogeneous highway scenario to evaluate DCC adaptability to varying density and CL conditions

Table 20: Configuration parameters for the heterogeneous highway scenario

Parameter	Value	Default
Highway Length	1 000 m to 50 000 m	10 000 m
RSU Inter-Location	50 m to 500 m	100 m
Vehicle size	2 m × 5 m	2 m × 5 m
Arrival Rate	Erlang (λ,k)	k = 1 λ = inter-distance time [s]
Flow density class	Dense (λ = 2 s)	Dense
Contra-flow density class	Sparse (λ = 20 s)	Sparse

7.3.2.2 Heterogeneous clustered highway

This scenario aims at testing DCC responsiveness (i.e. how quickly DCC algorithms may response and re-converge after sudden changes in CL conditions). It extends the highway scenario, keeps the contra-flow as sparse, but introduces clusters/platoons of vehicles on the direct flow. DCC algorithms are evaluated on the contra-flow vehicles as well as on the RSU, but not on the direct flow. Clusters of vehicles create sudden and localized dense DCC conditions, immediately followed by very sparse DCC conditions. The scenario is depicted on Figure 28, whereas the parameters are listed in Table 21.

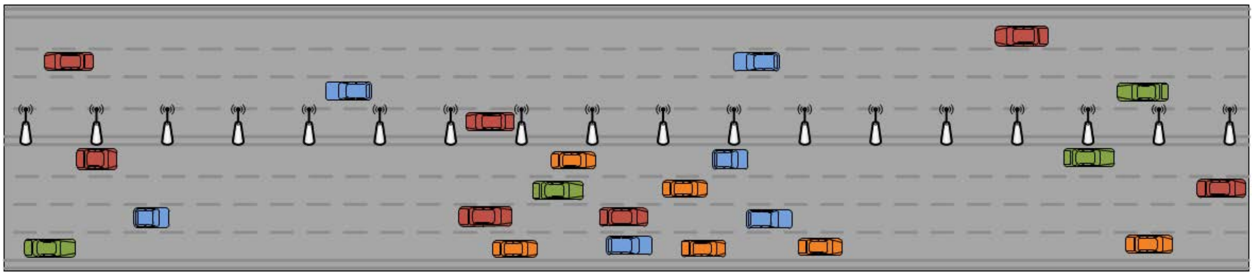

Figure 28: Heterogeneous clustered highway scenario

Table 21: Configuration parameters for the heterogeneous clustered highway scenario

Parameter	Value	Default
Highway Length	1 000 m to 50 000 m	10 000 m
RSU Inter-Location	50 m to 500 m	100 m
Vehicle size	2 m × 5 m	2 m × 5 m
Arrival Rate	Erlang (λ,k)	k = 1 λ = inter-distance time
Flow density class	Cluster: λ = 2 s Inter-cluster: λ = 20 s	λ = 2 λ = 20 s
Contra-flow density class	Sparse (λ = 20 s)	Sparse

7.3.2.3 Heterogeneous elevated highway

The elevated highway scenario is in configuration very similar to the heterogeneous highway. It corresponds to one highway configured to be dense and a second highway crossing over the first that is configured to be sparse. Parameters from Table 20 are used by considering 3 lanes and 2 directions each per highway.

7.3.3 Weak LOS scenarios

7.3.3.1 Blind intersection (static obstacles)

The objective of this scenario is to test the resilience of the DCC algorithms to static NLOS scenario. In particular, it tests if the NLOS conditions do not lead any DCC algorithms to violate safety conditions, such as reducing the TX power too low and detecting an approaching vehicle too late.

Weak LOS conditions are created by creating one blind intersection. On the horizontal street, one direction of the road has dense traffic, while the other direction has sparse traffic. Any vehicle on that sparse lane approaches the intersection and might have a collision with vehicles coming from the blinded crossing road. DCC algorithms are therefore tested both on the *sparse* horizontal and blind vertical streets, but not on the horizontal dense direction. Such a scenario is depicted on Figure 29. The parameters are taken from the heterogeneous highway condition (see Table 20), adapted to an X-shape intersection and, where radio-blocking buildings are present, at each side of the intersection.

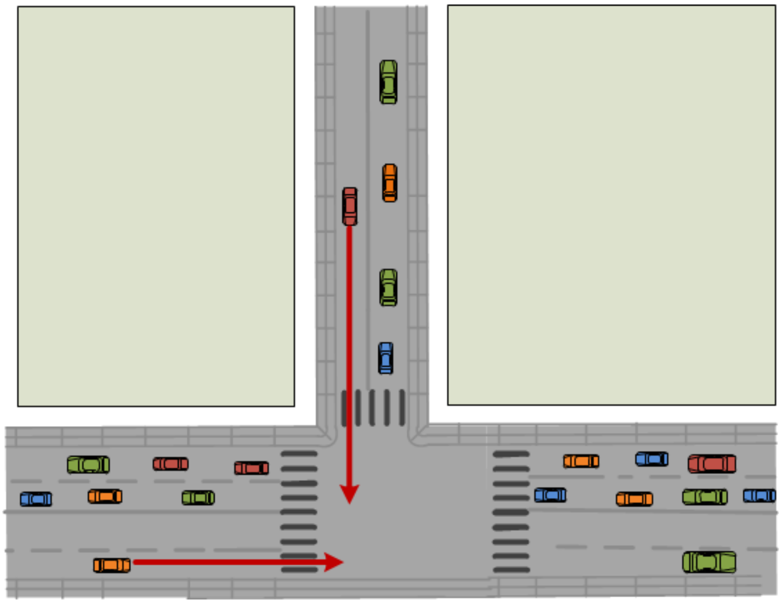

Figure 29: Radio-blocking blind intersection scenario

7.3.3.2 Blind highway (mobile obstacles)

The objective of this scenario is to test the resilience of the DCC mechanisms in mobile NLOS situation with significant hidden node conditions. This scenario can be adapted to the homogeneous or heterogeneous highway scenarios. The scenario aims at evaluating the impact of mobile NLOS situations created by vehicles shadowing the transmissions of other vehicles.

Figure 30 depicts such a situation, where two vehicles (obstacle 1 and obstacle 2) are temporarily blocking the communications between TX and RX. The influence of mobile obstacles can be modelled by a random probability to face such obstacles and adapting the fading environment. Parameters and models for this scenario can be found in [i.17].

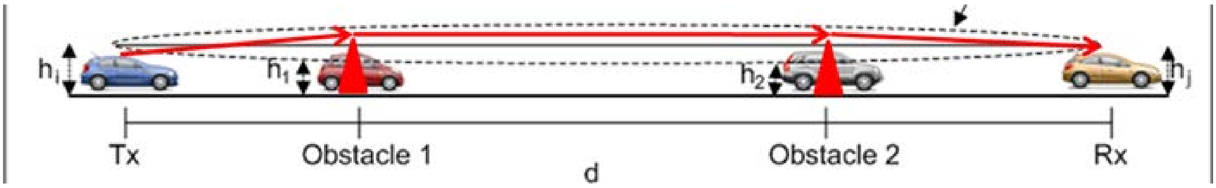

Figure 30: Mobile radio obstacles created by two vehicles between two TX ITS-Ss

7.4 Communication scenarios

The present clause provides a set of standard communication parameters that correspond to reference communications scenarios. Some parameters are common to all scenarios and are provided in Table 22. The CAM messages are transmitted on the EDCA queue 3, while DENM are on EDCA queue 1.

Table 22: Default communication parameters for all scenarios

Parameter	Value
CAM transmission ranges (in Time)	[0,6 ms - 0,8 ms - 1 ms]
CAM 'minimum' Tx Rate (R^{tx})	1 Hz
CAM default Tx Rate (R^{tx})	10 Hz
CAM triggering conditions: changes in position - speed - acceleration	5 m - 2 m/s - 1 m/s^2
Default Tx Power (P^{tx})	23 dBm
Tx Power approaching CEN DSRC Toll Booth	10 dBm
CAM Routing	SHB
EDCA Queue / TC	1 DENM / 3 CAM
$ED^{threshold}$	-95 dBm
Modulation Schema	QPSK ½ 6 Mbit/s
Antenna Pattern	Omnidirectional, gain = 1 dBi
Access Technology	ITS G5A
ITS G5 Channel	CCH

In order to be able to evaluate DCC algorithms following the recommendations of the present document, communications scenarios with increasing granularity and complexity are provided.

The first scenario considers that all ITS-S are in communication range, which means that all ITS-S can receive transmissions of each other and hidden nodes are not present. Considering either homogeneous or heterogeneous distributions of ITS-S, this scenario can provide a controlled homogeneous CL between ITS-S. Accordingly, fading will be limited to power attenuation and the physical size of the simulated area is limited to the theoretical CR of the ITS-Ss. More details are provided in Table 23.

The second scenario relaxes first scenario in terms of communication range and adjusts the transmit power and required vehicular density so that vehicles are not all in communication range. The practical aspect is that the mobility scenarios do not need to be harmonized with the communication scenarios, which leaves more freedom for testing purpose. More details are provided in Table 23.

The third scenario introduces fading of the received signal strength in various levels of granularities: correlated shadow fading and fast fading, both with the possibility to include shadowing from mobile radio obstacles. More details are provided in Table 24.

Table 23: Scenario 1 and scenario 2 - communication scenario - no-hidden node

Parameter	Value
Tx Power	Fixed 23 dBm
Fading	LogDistance, Exponent: 2
Target CL	65 %

Table 24: Scenario 3 - communication scenario - fading

Parameter	Value
Tx Power	23 dBm / 10 dBm CEN DSRC
LOS Fading Attenuation	LogDistance, Exponent: 2
LOS Fading Shadowing	Correlated shadowing, decorrelation distance: 20 m
LOS Fading Fast Fading V2V	Nakagami-m, m = 3
LOS Fading Fast Fading V2I	Winner B2 LOS
NLOS Fast Fading static obstacle	Winner B2 NLOS
NLOS Fast Fading dynamic obstacle	GEMV2

7.5 General functions

The present clause describes controllable and measurable DCC reactions, when a DCC algorithm is subject to a particular trigger. Triggers are related to particular application-related contexts and are listed in Table 25, unless a particular placeholder for application-based DCC function is defined.

Table 25: General DCC function to be followed by DCC mechanisms based on the following document

General Functions		
Name	**Trigger**	**Expected Output**
Vehicle in Dense Traffic	a) Vehicle approaches the traffic jam	Vehicle transmits at maximum power (23 dBm) and at a DCC-controlled rate.
	b) Vehicle in traffic jam	Vehicle reduces transmit power to low power (10 dBm); DCC-controlled rate is adjusted.
	c) Vehicle leaves traffic jam	Vehicle increases its transmit power to 23 dBm and its DCC-controlled rate.
Vehicle in Contra-Flow - Light Traffic	a) DUT senses dense CL, created by a dense traffic on other direction. Its speed indicates it is not in dense traffic (its direction is not congested)	Vehicle keeps transmit power to 23 dBm, adjusts its transmit rate to the channel conditions.
TTT Road Tolling Coexistence	a) Ego vehicle approaches a TTT Road Tolling plaza.	Vehicle reduces its transmit power to 10 dBm and adjusts its transmit rate according to the DCC algorithm.

None of the functions make any assumption on the underlying scenario. The strategy is, therefore, to evaluate the functions described in Table 25, on scenarios of varying complexity. Table 26 provides a description of four potential scenarios to be used in cooperation with Table 25.

Table 26: Set of scenarios to be used to evaluate the DCC functions

Scenarios	Description	Characteristics
Scenario 1.a	Perfect homogeneous neighbourhood	All vehicles see all vehicles - no hidden node - perfect local CBR reports. Global CBR identical to local CBR.
Scenario 1.b	Imperfect homogeneous neighbourhood	As scenario1.b, but with controllable errors in CBR reports.
Scenario 2.a	Perfect heterogeneous neighbourhood	Heterogeneous local CBR - CBR exchange required - hidden node likely - perfect global CBR reports.
Scenario 2.b	Imperfect heterogeneous neighbourhood	As scenario 2.a, but with controllable losses of neighbour CBR reports and errors in global CBR.

7.6 Key Performance Indicators

The DCC algorithms implemented according to the specifications of the present document may have different behaviour and be difficult to compare. Accordingly, the DCC algorithms are evaluated on their capabilities to fulfil Key Performance Indicators (KPIs).

DCC KPIs are specific for each layer of the ETSI ITS architecture: DCC_ACC, DCC_NET, DCC_FAC, DCC_CROSS. An example of DCC_CROSS KPI is described in Table 27, including suggested success/failure criteria.

Table 27: DCC_CROSS KPI, including success/failure criteria

KPI: Communications		
Hypothesis: DCC lead to fair channel access for all ITS-S.	**Performance Indicator:** Fairness	**Success Criteria:** The estimated variance around the sample mean of the CAT by all ITS-S in close neighbourhood of an ITS-S does not exceed 10 %
CL does not reach a congested case.	CBR	**Success Criteria:** The CL does not exceed the CBR_{limit} load by more than 10 %
DCC does not generate unstable R^{tx} P^{tx} adjustments.	Stability	**Success Criteria:** At stability, the gradient of P^{tx} or R^{tx} is not inverted more than 10 % over 10 CBR reports
NOTE 1: Assuming x_i as an observation of a random variable X_i representing the CAT of an ITS-S, the sample mean of the CAT is given by: $\mu(n) = \Sigma_n x_i / n$, where n represents the number of observations. The variance of the sample mean is given by: $\sigma^2 (n) = \Sigma_n (x_i - \mu(n))^2 / (n-1)$. NOTE 2: The 'close neighbourhood' is defined in the present document as the immediate 1-hop neighbours. NOTE 3: An alternate fairness indicator can be represented by measuring the estimated variance around the sample mean of the CL, which in that should not exceed 10 % for the Fairness test to be a success.		

8 Initial simulation results

8.1 Introduction

The present clause evaluates different DCC implementations fulfilling the guidelines identified in the present document to fit the minimum DCC KPI.

8.2 Performance evaluation of reactive and linear adaptive DCC mechanisms

8.2.1 General

As described in Annex A, DCC has two types of approaches: reactive and adaptive. The reactive approach is based on a finite numbers of DCC states. Each of them corresponds to a restriction of the usable R^{tx} on the channel. The linear adaptive approach sets a target CL and then adapts positively or negatively the R^{tx} to reach the target CL. None of the two approaches adjust P^{tx}.

Fairly comparing both approaches is difficult, as they are based on fundamentally different strategies. The present clause provides initial evaluation of their capabilities to fulfil minimum DCC KPI. The first DCC KPI considered aims to be able to adapt the transmit parameters to control the CL in order to not overtake a given threshold.

8.2.2 Scenario description

The reactive and the linear DCC adaptive approaches are evaluated and compared. First, their capability to control the CL under extremely dense highway scenario is assessed. The highway scenario has been configured so that it corresponds to a **Highway LoS grade F**, i.e. corresponding to 'extreme traffic condition' from Table 18. The highway length is only 1 000 m long and all vehicles are static. It has been configured to reach the LoS F considering 418 vehicles transmitting at 23 dBm.

The generic '1D Highway' scenario under the 'extreme' traffic conditions from Table 19, as well as the 'simple fading-no hidden node' communication scenario from Table 23 have been selected. Shadow or fast fading have purposely not been included, as fading reduces congestion and would alter the scalability test. The complete simulation parameters are listed in Table 28.

Table 28: Simulation Parameter for the Evaluation of the reactive DCC algorithm w.r.t scalability (dense highway)

Parameters	Value
Mobility	
Scenario	1D Highway (see Table 19)
Density	Extreme (see Table 18)
Lanes in-flow	3
Lanes contra-flow	3
Length	1 000 m
Minimum Gap	10 m
Number of vehicles	418 vehicles
Communication	
Scenario	Simple Fading (see Table 23)
CAM packet size	400 bytes
Tx Power (default)	23 dBm
$ED^{threshold}$	-96 dBm
Tx Rate (default)	5,56 Hz
DCC Parameters	
DCC CL Window	100 ms
DCC CL sampling rate	1 000 Hz
Reactive DCC states	See Table 29
Adaptive DCC Target CL	60 %
Linear Adaptive DCC Alpha/Beta	0,5 / 0,5
Simulation Time	7,6 s

Table 29: DCC Reactive Parameters - T_{off} vs. CL for each DCC state

States	*CL* (%)	T_{off} (ms)	R^{tx} (Hz)
Relaxed	0 % ≤ CL< 19 %	60	16,7
Active_1	19 % ≤ CL < 27 %	100	10,0
Active_2	27 % ≤ CL < 35 %	180	5,6
Active_3	35 % ≤ CL < 43 %	260	3,8
Active_4	43 % ≤ CL < 51 %	340	2,9
Active_5	51 % ≤ CL < 59 %	420	2,4
Restricted	CL ≥ 59 %	460	2,2

8.2.3 Performance evaluation results

The performance results of the reactive and the linear adaptive DCC are shown separately in two figures. Figure 31 illustrates the CL as function of the simulation time. Although vehicles are static, noise in the CL measurement (imperfections) as well as instability and chain reactions on the DCC state transitions might lead to a time evolution of the CL controlled by the reactive DCC mechanism. Figure 31 illustrates this aspect.

When DCC is not activated, the channel rapidly becomes congested up to 90 % of the total CL. Small oscillations may be observed on the CL measurements of the order of up to 10 %, which can be explained from the rather low CL sampling rate of 100 Hz. Such low rate leads to missed transmission times (air time T_{on} of 1 ms and less) and accordingly, leads to DCC CL oscillations between high and low loads. Although such phenomena cannot be ignored in real deployments, it is here yet a simulation artefact. Perfect CL estimation would require channel sampling at the OFDM symbol rate. Such rate is impossible in packet-level network simulators (e.g. ns-3), first as OFDM symbols are not represented, and second as such sampling rate would require significant simulation resources. Accordingly, the current approach samples at a reduced sampling rate compared to what would be available on ITS-G5 chipsets. An enhanced CL implementation is currently being developed that would reduce such oscillations. These oscillations certainly have an impact on the DCC algorithms. But it is also beneficial, as CL measurements in real deployments will also be subject to measurement errors either from the local CBR measured, or from the Global CBR cooperatively exchanged in the neighbourhood.

When the reactive DCC algorithm is activated, Figure 31 shows that by restricting the available transmit rate on the channel, the algorithm is capable of controlling the CL to remain relatively low. The oscillations can be interpreted as a consequence of the oscillations on the CL measurements. The amplitude also indicates an artefact in the DCC state transitions. It should be noted that in this simulation scenarios all vehicles are in communication range (no hidden nodes), and, accordingly, distributed and unsynchronized decisions in the reduction on the TX rate could lead to nodes reducing the R^{tx} on the channel, then measuring a too low CL and re-increasing the R^{tx} again. More simulations are required in order to confirm the observation.

Figure 32 depicts the reactive DCC state distribution, which confirms that all states are widely used.

Figure 33 illustrates the linear adaptive DCC algorithm under a heavy CL and considering a target CL of 60 %. Although additional simulations are required, these early results show the convergence of the linear adaptive DCC toward the target CL. The convergence is rather slow, as it requires 8 s to 10 s to converge, but is the consequence of the iterative transmission adjustment at each CL digest report (100 ms). One aspect that will need to be checked is the impact of the DCC CL oscillations on the linear increase/decrease of the linear adaptive DCC. When a small relative difference between the target CL and the local measurement is reached, CL oscillations greater than the relative difference could lead to oscillations in the increase or decrease of the R^{tx}. Further simulations will be conducted to evaluate this aspect.

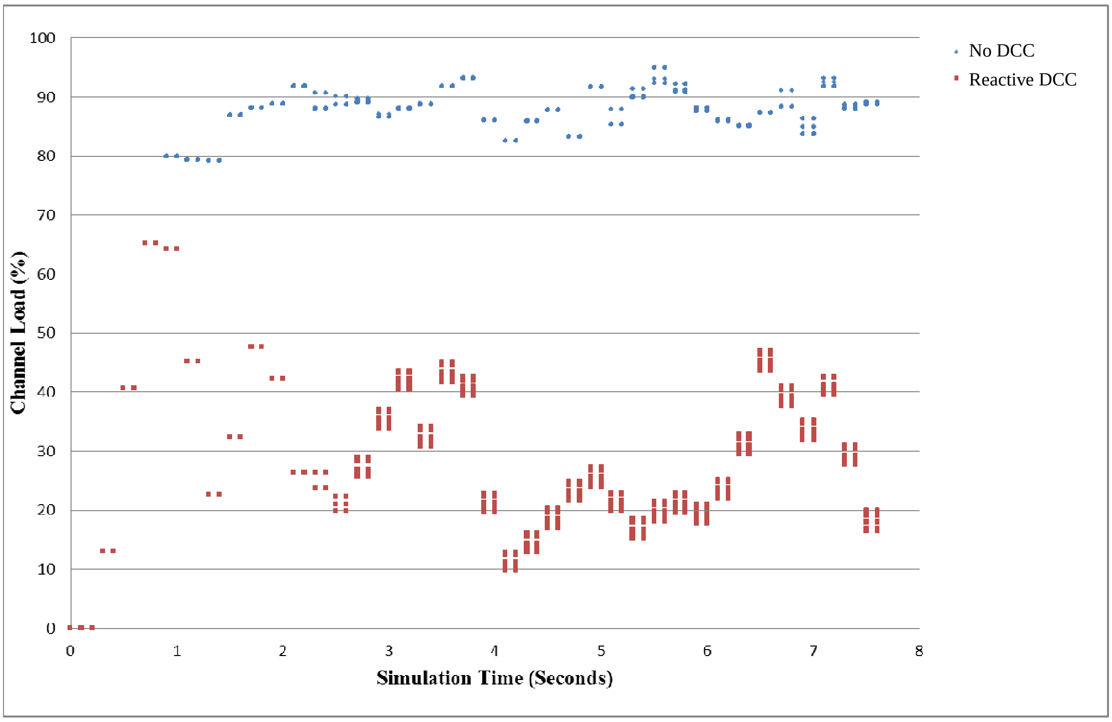

Figure 31: The CL in (%) over time in (second) reactive DCC in a very dense Highway scenario (LOS F)

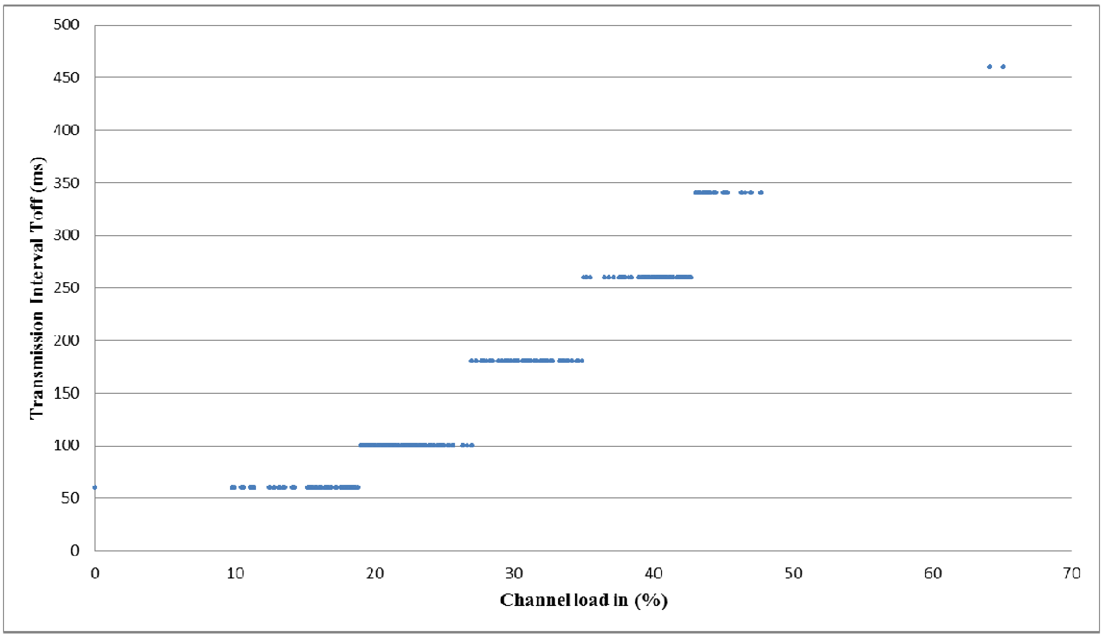

Figure 32: The transmission interval T_{off} in (milliseconds) vs. the CL in % in a very dense Highway scenario (LOS F)

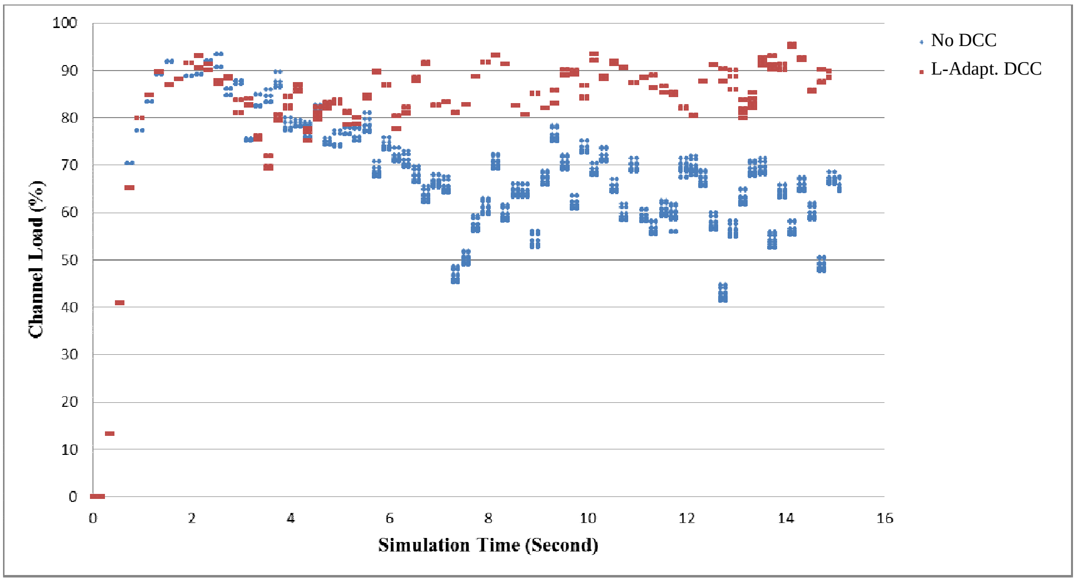

Figure 33: CL in % over time in seconds for linear adaptive DCC in a very dense Highway scenario (LOS F)

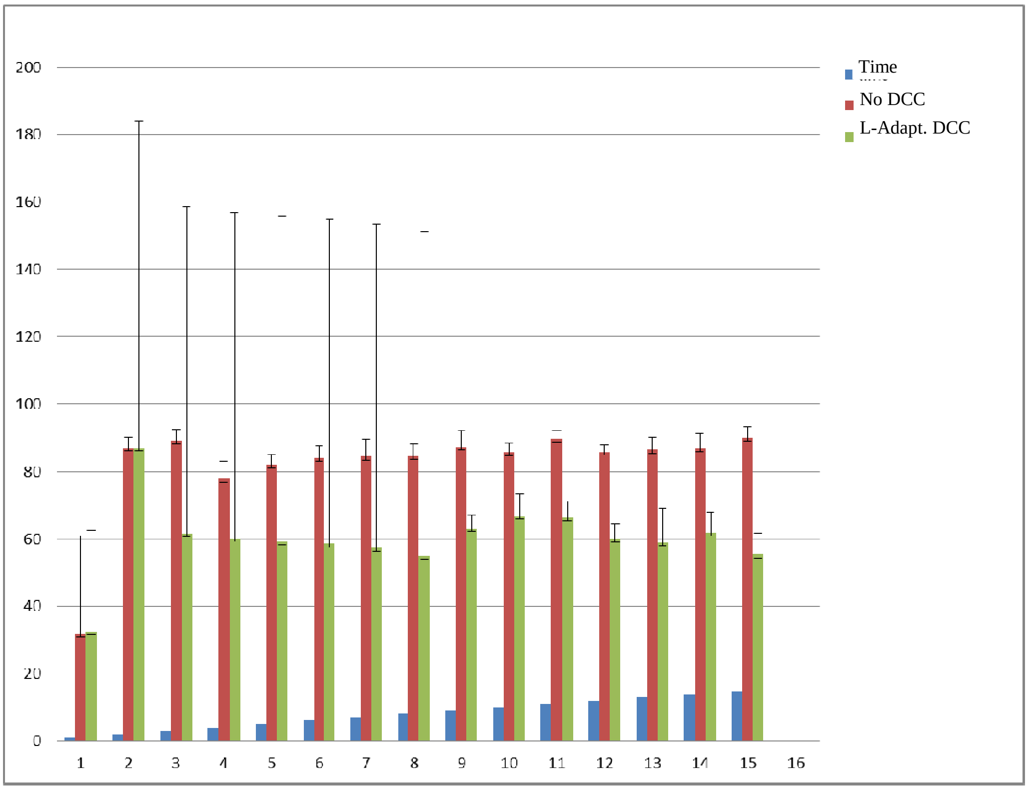

Figure 34: Average CL linear adaptive DCC in a very dense Highway scenario (LOS F)

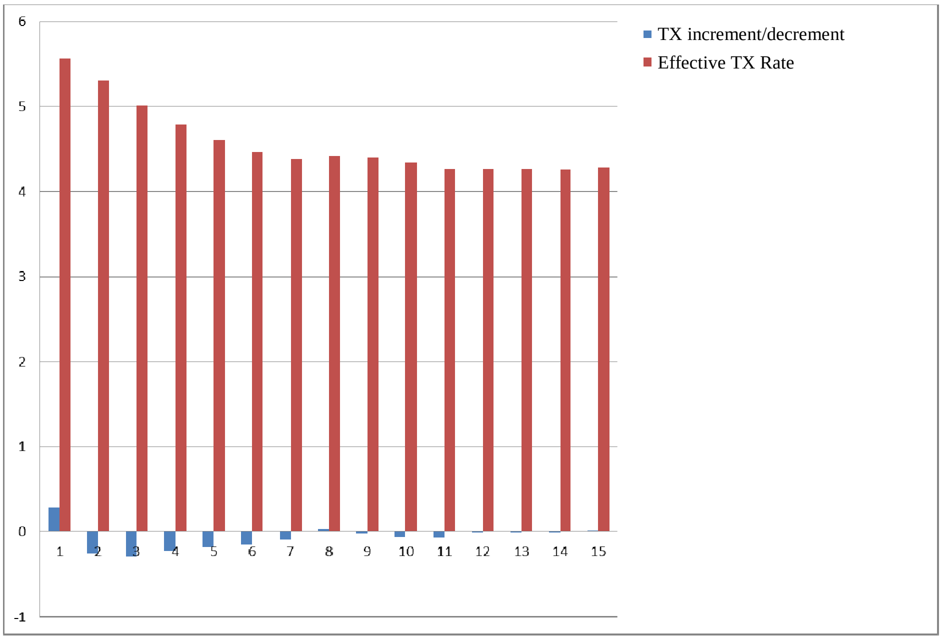

Figure 35: Message transmit rate (Hz) linear adaptive DCC in a very dense Highway scenario (LOS F)

8.2.4 Discussion on initial performance evaluation

Although results provided in the previous clause are only preliminary, they can still be tested against the DCC KPIs:

- **Fairness:** As a perfect neighbourhood scenario is considered (no hidden nodes, all ITS-S in communication range of each other), variations of CL may only come from sampling errors. When DCC algorithms are not activated, the variance of the CL is approximately 8 %, which is less than 10 % as specified in the CL KPI in Table 27. The test is considered as PASSED when the reactive DCC is activated, the variance of the CL is far more than 10 %. In such condition, the reactive DCC test is considered as FAILED. When the linear adaptive is activated, the CL oscillates around the target CL by approximately 10 % once converged (after 8 seconds). The test for linear adaptive DCC is PASSED.

- **CBR:** Both reactive and linear adaptive DCC algorithms managed to reduce the CL below the maximum CBR. The test for both DCC algorithms is PASSED. Note that the linear adaptive also managed to converge to a target CL of 60 % after 8 seconds.

- **Stability:** Cannot be tested, as results were not available.

Summarizing, both the reactive DCC and the linear adaptive DCC algorithms manage to efficiently control the CL to remain below a CBR limit. This is the major success indicator.

The reactive DCC algorithm generates instability in the DCC Flow control function. This may be explained by the fact that once a DCC state is reached, the T_{off} is increased. As all nodes are in communication range and have the same CL, they all reduce their contribution to the CL. Accordingly, at the next sampling time, the CL is below the previous DCC state, which in turn make DCC to reduce the T_{off} again for all nodes. Also, as the 418 nodes are all in communication range, a tiny extra CL contribution from all nodes may accumulate and result in a large global increase in the CL. In order to evaluate the impact of such oscillations, the reactive DCC algorithms should be evaluated based on application metrics, such as the IRT.

The linear adaptive DCC algorithm takes time to converge (approximately 8 s), which limits its capabilities to converge in scenarios with heterogeneous and fast changing mobility and communication conditions. The impact of such convergence time need be evaluated on more advanced scenarios, such as the heterogeneous highway, the clustered highway, or the elevated highway scenarios both in terms of CL as well IRT.

Annex A: DCC algorithms

A.1 General DCC types: reactive and adaptive

There are a variety of approaches to Decentralized Congestion Control (DCC). Among those that use CBR as an input, two general classes of DCC can be identified, which are referred to as Reactive and Adaptive. The present annex explains the difference between these approaches.

The main distinction between the Reactive and the Adaptive class is illustrated in Figure A.1. In the upper part of the figure, a DCC function uses the CBR directly in order to determine the current value of one or more control variables, for example message rate, transmit power, etc. Those variables impact the communication behaviour of the device, which in turn feeds back to influence the CBR. The CBR observed at a device is a function of the aggregate communication behaviour of all C-ITS-s devices operating around it.

In the lower part of the figure, a DCC function compares the current CBR to a target CBR value and then uses the difference between those two, the adaptation error, to adjust one or more control variables. As in the Reactive approach, the change in control variables at this ITS-S and its neighbours feeds back to influence CBR. The CBR target is either fixed, or slowly changing relative to the adaptation of the control variable.

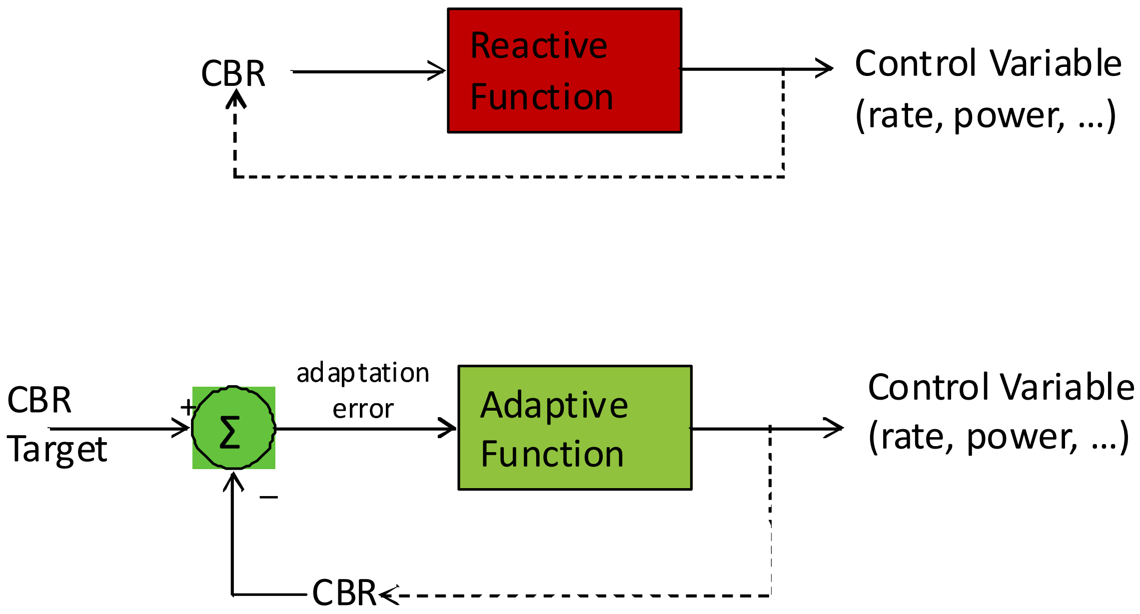

Figure A.1: Comparison between Reactive and Adaptive DCC

The reactive approach depends on the CBR evaluation and does not depend on previous values of the control variables, other than perhaps through some minor hysteresis. The function might take the form of a state-based table lookup or the execution of a formula. For a well-designed Reactive Function operating in a given device topology, the steady state CBR depends heavily on the ITS-S density, with higher density leading to higher CBR.

In contrast to the Reactive Function, the Adaptive Function uses not only the adaptation error, but also the prior control variable values, as it actively drives the CBR toward the target. The point of using an Adaptive approach is to achieve a steady state CBR that is approximately independent of ITS-S density. It is well known that the throughput of IEEE 802.11/ITS-G5-based systems under increasing CL reaches a maximum value and then falls as the channel becomes increasingly saturated (for example, see Bansal, VT Mag 12/2014 [i.18]). An Adaptive DCC that sets the CBR target based on the maximum channel throughput and controls the CBR independent of the network topology has the desirable property of minimizing the interval between successful receptions from a given sender.

The behaviour of CBR as a function of an creasing ITS-S density (mentioned as devices) is shown in Figure A.2 for three approaches: No DCC, Reactive DCC and Adaptive DCC. When there is no DCC present the CBR will continue to increase with increasing number of ITS-S until the channel is saturated. In Reactive DCC, the CBR will continue to grow but not at the same pace as in the case with when there is no DCC. Algorithms based on an Adaptive DCC will strive towards a CBR goal and stay around this CBR goal. It assumes all three approaches have the same CBR at one given ITS-S density. From that point, the normal growth in CBR for ITS-G5 systems is observed in the "No DCC" curve, which represents a system for which the communication variables do not depend on CBR. The "Adaptive DCC" system achieves a CBR that is independent of ITS-S density. In the "Reactive DCC" case, CBR still grows with the ITS-S density, but the "Reactive DCC" modifies the usable resources parameters in order to slow the rate of growth.

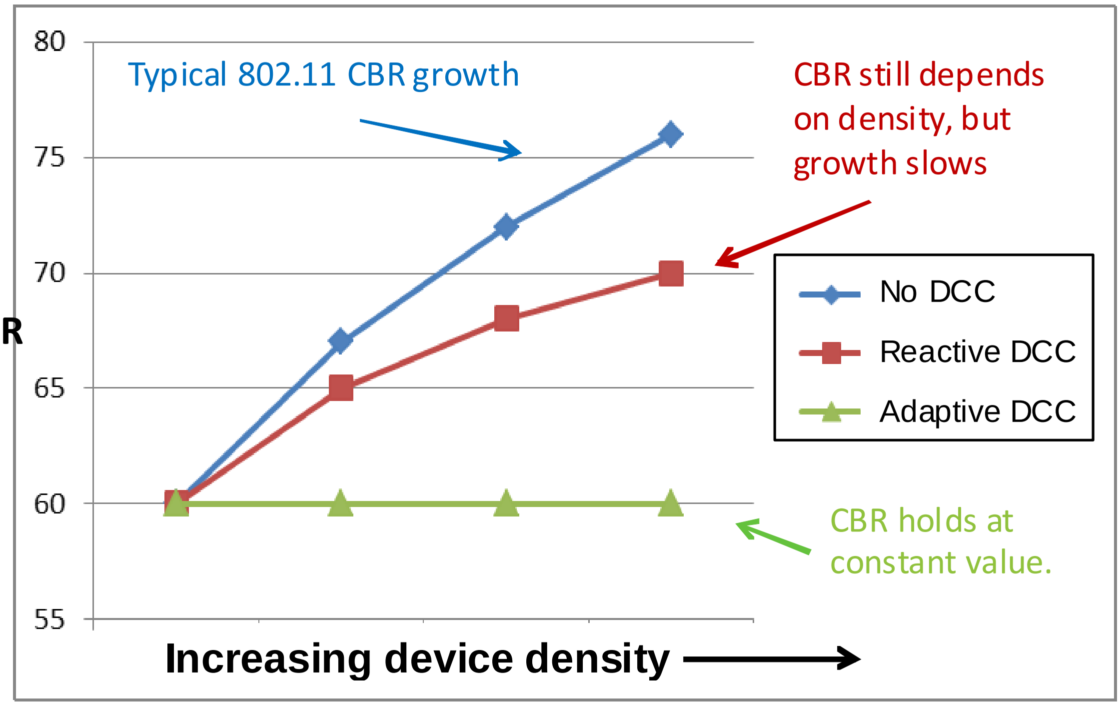

Figure A.2: Illustrative CBR vs. Density plot for various DCC approaches

A.2 Reactive DCC class

Within the class of reactive approaches, there are two approaches for the reactive function: adjusting the transmit rate, or adjusting a DCC flow control filter to limit the contribution of a node's packet to the channel load.

Although the first approach implicitly reaches the same objective as the second approach, the first requires a control of the packet generation that is not always possible, whereas the latter does not have any assumption on packet generation.

Strictly speaking, the reactive DCC mechanism does not control the transmit rate, as it does not change the rate with which packets are generated and does not aim at transmitting as many packets as the DCC flow control mechanism would allow. It only performs flow control, i.e. filters and restricts the access to the wireless medium between T_{off} and T_{on}. Still, it is possible to complement a reactive DCC mechanism with adjustments in the packet generation rate.

The DCC mechanism described in ETSI TS 102 687 [i.2] classifies the DCC conditions in three main DCC states as a function of the CL: *relaxed, active, restricted.* The *active* DCC state may be subdivided in configurable sub-states (*active*$_x$). In order to provide a finer flow control on the CL, ETSI TS 102 687 [i.2] additionally subdivides the active state in five sub-states. Table A.1 illustrates the relationship between the states and the CL.

Table A.1: Reactive DCC - DCC states and corresponding CL

States	*CL* (%)	T_{off} (ms)	R^{tx} (Hz)
relaxed	0 % ≤ CL< 19 %	60	16,7
active_1	19 % ≤ CL < 27 %	100	10,0
active_2	27 % ≤ CL < 35 %	180	5,6
active_3	35 % ≤ CL < 43 %	260	3,8
active_4	43 % ≤ CL < 51 %	340	2,9
active_5	51 % ≤ CL < 59 %	420	2,4
restricted	CL ≥ 59 %	460	2,2

For example, when the CL exceeds 19 %, then the DCC reactive mechanism moves from the relaxed state to the *active 1* state and so on. Each DCC state corresponds to a DCC flow control state, which is specified by adjusting the T_{off} idle time, where the DCC flow control would block packets from accessing the channel. The T_{off} idle time, as well as the T_{on} transmit time can be adjusted such that the all neighbouring ITS-S have a fair share of the channel resources. Mechanisms as those described in clause 5.3 may be used to set the optimal value of the Idle time T_{off} and T_{on} for each DCC state. The values selected by the reactive DCC and the corresponding TX rate are also listed on Table A.1.

NOTE: The reactive DCC flow control could be implemented by a leaky bucket adjusted to the T_{off} values, such that regardless of the packet arrival rate at the flow control block, the exit rate of the leaky bucket would be adjusted to the DCC state.

When emergency packets need to be transmitted even during a T_{off} idle time (e.g. high emergency DENM), the reactive DCC class tolerates a temporary violation of the T_{off} idle time. In order to limit the congestion on the channel from the burst of such extra packets, the reactive DCC class controls the number and arrival rate on the ITS-G5 radio.

The implementation of such emergency flow control is out of scope of the present document and not explicitly described by the present reactive DCC clause, but could be done by a simple token bucket adjusted to the emergency R^{tx}, such that regardless of the packet arrival rate at the flow control block, the exit rate of the token bucket would be adjusted to the rate as well as number of successive emergency packets tolerated.

A.3 Adaptive DCC mechanisms

Within the class of adaptive DCC mechanisms, two categories of adaptation algorithms exist: Binary Control and Linear Control. This label refers to the way in which the adaptation error is used to modify communication variables. A Binary Control only considers the arithmetic sign of the error, i.e. whether the CBR is above or below the CBR Target. A Linear Control uses the full precision of the adaptation error, both the sign and the magnitude.

Many examples of Binary Adaptive Control algorithms for data networking exist. The best known algorithm is the Additive Increase Multiplicative Decrease (AIMD) algorithm, a variation of which is part of the Internet's Transmission Control Protocol (TCP). In AIMD, if the error is positive ($CBR^{target} > CBR(t)$), it is desired that the CBR grows, so the control variable is increased by an additive offset independent of the current value. If the error is negative, the CBR should come down and the control variable is decreased to a given fraction of its current value. The AIMD principle is illustrated in the following equation, for the case that a device *j* adapts its rate variable $R^{tx}(t)$ over time:

$$\text{If } (\mathrm{CBR}(t) \geq \mathrm{CBR}^{target}) \tag{A.1}$$

$$R^{tx}(t+1) = R^{tx}(t) + \mathrm{AI}$$

$$\text{Else}$$

$$R^{tx}(t+1) = \mathrm{MD} \times R^{tx}(t),$$

where AI and MD are the additive increase and multiplicative decrease parameters of the algorithm, respectively.

AIMD has been shown to have robust convergence and generally good fairness properties [i.20]. Fairness means that in a decentralized environment, devices observing the same conditions (CBR) will converge to the same communication variable value. One undesirable feature of AIMD, and all binary controls, is that the control variable converges to an oscillatory limit cycle in steady state, rather than to a constant value. This oscillation stems from the fact that at each adaptation time the algorithm always moves the variable, either up or down. The adapted variable cannot remain constant. The size of oscillation can be controlled through choice of the additive increase and multiplicative decrease parameters, but smaller steady state oscillations are associated with longer convergence times, so there are practical limits on this control.

Linear Control algorithms provide improved steady state performance compared to Binary Control algorithms. By using the full precision of the adaptation error, the algorithm takes smaller and smaller steps as it converges and asymptotically approaches a constant value in steady state. One example of a Linear Adaptive Control uses the following update equation for rate *r(t)* at device *j:*

$$R^{tx}(t+1) = (1-\alpha) \times R^{tx}(t) + \beta \times (CBR^{target} - CBR(t)), \quad (A.2)$$

where α and β are parameters of the algorithm. Another feature of Linear Control algorithms is that principles of Linear System Theory can easily be applied to prove important properties, such as stability, convergence and fairness.

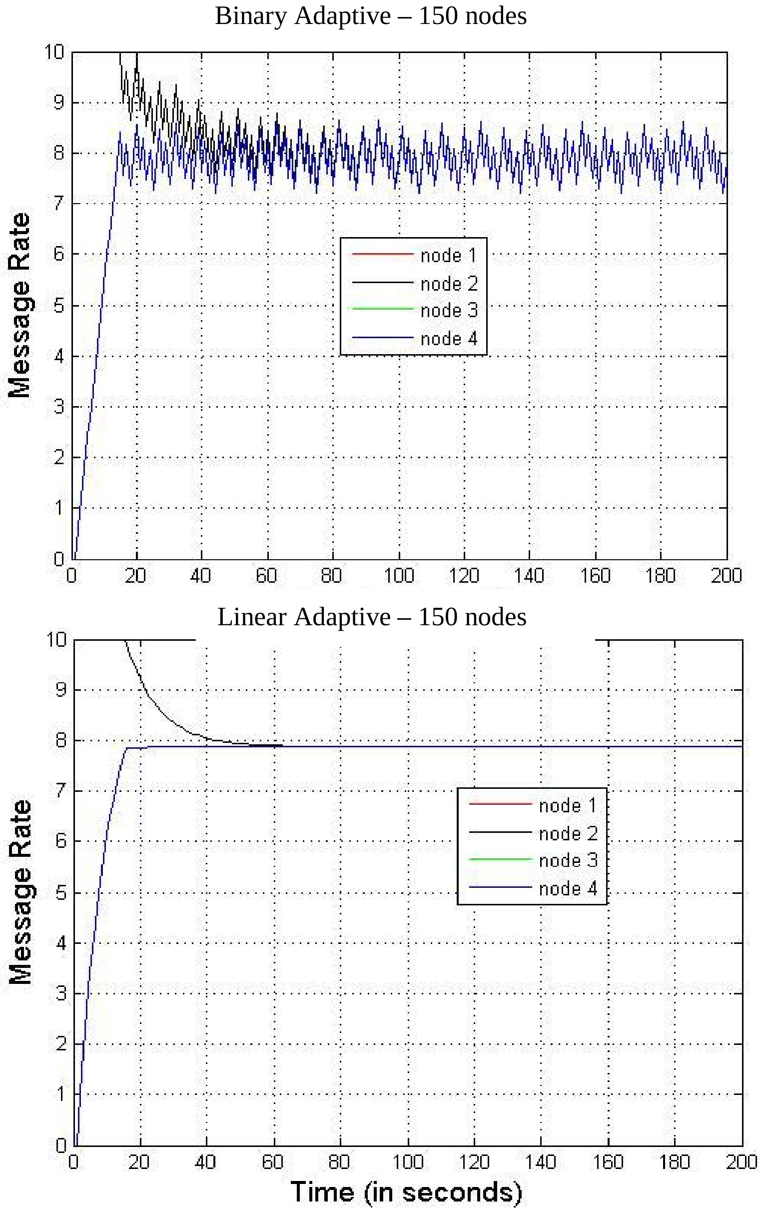

Figure A.3: Comparison of steady state behaviour for Binary and Linear Control algorithms

Figure A.3 demonstrates the difference in steady state behaviour between a typical Binary Control and a typical Linear Control algorithm. The graph shows simulated control on the message rate R_M for 150 devices using a CBR^{target} of 60 %. Some of the 150 devices have an initial message rate R_M of 0 , while the rest have initial R_M equal to 10 messages per second. The R_M versus time is shown for four representative devices in each case. Both control mechanisms achieve fair convergence, that is the R_M comes together regardless of the initial condition. The R_M in the Binary Control algorithm exhibits typical steady state limit cycle oscillations, with peak-to-peak variations of about 1,5 messages per second. In contrast, all of the Linear Control message rates converge with no oscillations around the steady state. In a practical implementation, inaccuracies in the measurement of CBR will lead to small steady state variations even for the Linear Control, but these are random, not systematic and typically much smaller than the Binary Control limit cycle.

This annex has explained the difference between the class of Reactive and Adaptive DCC mechanisms and also between Binary and Linear approaches to Adaptive DCC. Several important features of both classes of DCC has been shown to indicate the asset and potential weaknesses of both classes. Implementation details are out of the scope of the present document.

Annex B: Simulation platforms

B.1 iTETRIS ITS platform

B.1.1 Introduction and general architecture

Simulating cooperative vehicular communication and ITS systems require the capability to jointly model vehicular mobility, wireless vehicular communications, in addition to implement and execute novel cooperative ITS applications. The present clause presents iTETRIS, a unique ETSI ITS compliant and open source simulation platform developed under the European FP7 Program (iTETRIS: an Integrated Wireless and Traffic Platform for Real-Time Road Traffic Management Solutions, http://ict-itetris.eu/) for investigating cooperative ITS systems and services. The architecture of iTETRIS is depicted in Figure B.1, which federates the traffic simulator SUMO, an ETSI ITS compliant extension of the network simulator ns-3 and an ITS application module around a control module, the iCS.

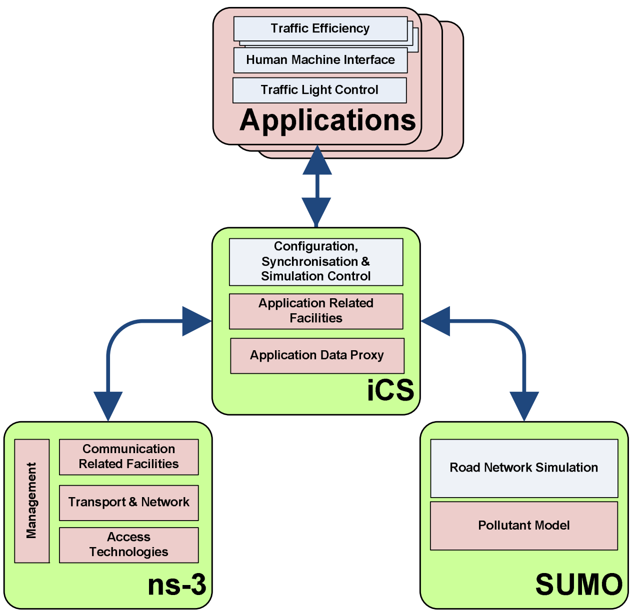

Figure B.1: General architecture of iTETRIS, containing three modules (ns-3, SUMO and ITS applications) interconnected by the iCS

The iTETRIS platform is available under GPLv3 license at the following website (http://www.ict-itetris.eu/10-10-10-community/). The major features of iTETRIS relevant to the scope of the present document are described next. Further details may be found in [i.16].

B.1.2 The network simulator ns-3 and its extensions for iTETRIS

ns-3 (http://www.nsnam.org/) is an open discrete-event simulation environment that been designed to be the successor of the popular simulator ns-2. Aiming to be more scalable and more open for extension, it significantly differs from ns-2 with its novel structural and modular implementation.

As illustrated in Figure B.2, ns-3 has been enhanced for iTETRIS with specific capabilities for vehicular communication that are briefly explained below:

- **Access Layer:** The ETSI ITS-G5 (IEEE 802.11-2012 OCB) has been integrated as another WLAN access technology, while a channel router module controls the multi-channel operation of ns-3 between three channels: CCH, SCH1 and SCH2. Additionally, a cellular module, UMTS, WiMAX and a broadcast channel DVB-H have been implemented in ns-3 for infrastructure-type communication. The selection of the appropriate communication technology is done via a module for technology seletcion, which indicates the interface to be used for transmission via a Communication Profile on a per-packet basis.

- **Network Layer:** A dual stack (IPv6, ETSI ITS GeoNetworking as defined in ETSI EN 302 636 [i.3]) is available. The ETSI ITS GeoNetworking protocol stack includes geographic addressing capabilities and multi-hop geographic routing.

- **Facilities Layer:** The facilities layer (as defined in ETSI EN 302 665 [i.10]) has been separated into two parts: the application facilities implemented in the iCS and the communication facilities implemented in ns-3. The latter are composed of three major blocks: the CAM/DENM message generators, the communication technology selector and the DTN module.

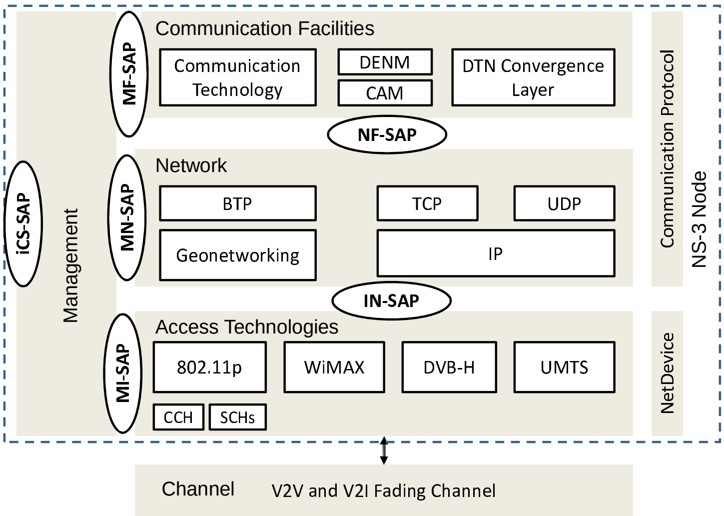

Figure B.2: Functionalities of ns-3 as extended by the iTETRIS simulator

ns-3 has also been extended by various wireless models covering fading specific for each technology or environment as depicted in Table B.1.

Table B.1: Fading Models as function of access technology in iTETRIS

Technology	Urban	Highway
ITS G5 V2V	WINNER B1	Nakagami-m (Cheng & Stancil)
ITS G5 V2I	WINNER B1	WINNER D1
WIMAX	WINNER C2	WINNER D1
UMTS	WINNER C2	WINNER D1
DVB-H	Okumura-Hata (Urban & Suburban)	Okumura-Hata (Rural)

B.2 IGOR

B.2.1 Introduction

The IGOR simulator can simulate the ITS-G5 MAC layer and the interference between ITS-G5 and TTT Road Tolling. The mobility simulator can be parameterized to represent different multi-lane traffic scenarios (no crossroads). The wireless channel model is deterministic and does not consider "non line of sight effects", i.e. no shading obstacles.

Several DCC and coexistence algorithms can be implemented to evaluate the system performance. This simulator is intended to be used to obtain results for the preparation of the technical study on validation setups.

B.2.2 Architecture

The simulator consists of the following parts:

- RF simulator:
  - Includes antenna models and radio propagation models (all validated by measurements).
- ITS-G5 Broadcast MAC layer simulator:
  - Simulates the behaviour of cyclic ITS-G5 broadcast messages for IEEE 802.11 [i.1] CSMA/CA.
- TTT Road Tolling protocol simulator:
  - Simulates the TTT Road Tolling transaction including retries, late response and multiple OBUs.
- TTT Road Tolling frame error evaluation:
  - The values provided by the RF simulator determine the TTT Road Tolling frame error probability by an empiric model.
- Mobility simulator:
  - Moves the vehicles and defines the road geometry.

The interconnection between the parts of the simulator is depicted in Figure B.3.

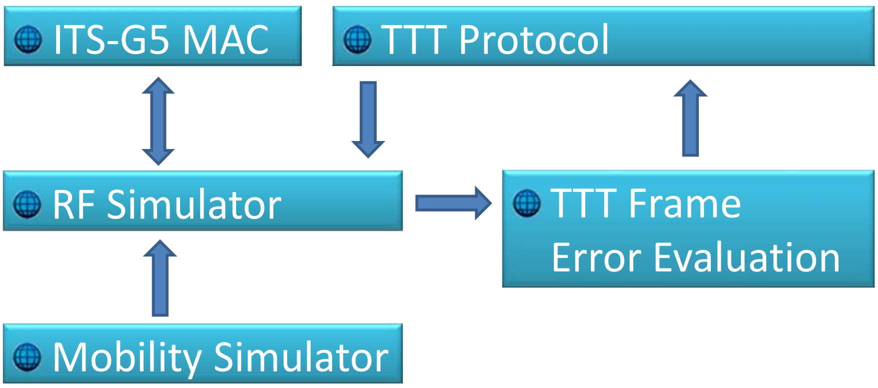

Figure B.3: IGOR Simulator architecture

B.3 Channel models

Channel Models are critical for the evaluation of wireless channel congestion and DCC transmit policies. A detailed coverage of available close-to-reality channel models may be found in ETSI TS 103 257 [i.15].

History

Document history		
V1.1.1	September 2014	Publication