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Contents

Intellectual Property Rights 6
Foreword 6
Modal verbs terminology 6
Executive summary 6
Introduction 7
1 Scope 10
2 References 10
2.1 Normative references 10
2.2 Informative references 10
3 Definition of terms, symbols and abbreviations 13
3.1 Terms 13
3.2 Symbols 14
3.3 Abbreviations 15
4 Considerations 17
4.1 Introduction 17
4.2 Message handling 17
4.3 Quality of Service improvement 18
4.4 The system context 19
4.4.1 Overview 19
4.4.2 Channel load 20
4.4.3 Access layer operation 21
4.4.4 Adjacent channel 21
4.4.5 Networking & transport layer operation 21
4.4.6 Applications, facilities layer and resource management 22
5 Decentralized Congestion Control optimization 22
5.1 Introduction 22
5.2 Decentralized congestion control in Release 1 23
5.2.1 Introduction 23
5.2.2 Overview of Release 1 DCC 23
5.2.3 Metrics 23
5.2.4 Limit imposed to the channel load 23
5.2.5 Release 1 DCC at the access layer and constraints to the algorithm 24
5.2.6 Release 1 DCC at the networking & transport layer 24
5.2.7 Release 1 DCC at the facilities layer 25
5.3 Critical analysis of Release 1 DCC 25
5.3.1 Introduction 25
5.3.2 Analysis of global CBR sharing 25
5.3.3 Analysis of the limit 25
5.3.4 Analysis of algorithms 28
5.3.5 Analysis of variables that impact congestion control 31
5.3.6 Analysis of multi-hop forwarding 32
5.4 Interference from adjacent channels 33
5.4.1 Introduction 33
5.4.2 Impact of interference from interoperable C-ITS in adjacent channels 33
5.4.3 Adjacent channel monitoring 35
5.4.4 Cross-channel resource management control 35
5.5 Modifications towards Release 2 35
5.5.1 Introduction 35
5.5.2 Radio resources at the facilities layer 35
5.5.3 Congestion control in Release 2 36
5.5.4 Information required by the resource management for the ALI selection 37
5.5.5 Overhead from protocol headers and security 37

5.5.6 Introducing a mechanism for the update of parameters 38
5.5.7 Networking & transport layer in Release 2 38

6 Application requirements 40
6.1 Introduction 40
6.2 Applications and message services 41
6.2.1 Introduction 41
6.2.2 Decentralized Environmental Notification Message 41
6.2.3 Cooperative Awareness (CA) Message 43
6.2.4 Collective Perception (CP) Message 44
6.2.5 MIM and MVM 45
6.2.6 Signal Phase and Timing Message (SPATEM) 45
6.2.7 MAP Message (MAPEM) 45
6.2.8 In Vehicle Information Message (IVIM) 45
6.2.9 Service Announcement Message (SAM) 45
6.2.10 Vulnerable road user Awareness Message (VAM) 46
6.3 Types of message services from RM perspective 46
6.4 Heterogeneous resource requirements 47
6.4.1 Same services but different resource needs 47
6.4.2 Different stations with different needs 47
6.5 Indications to message services 47
6.6 Conclusions 48

7 Resource management concepts 49
7.1 Introduction 49
7.2 Analogy with wired networks 49
7.3 Resource management architecture and its mechanisms 50
7.3.1 Overview 50
7.3.2 Admission control techniques 51
7.3.3 Dynamic bandwidth management techniques 52
7.3.4 Traffic shaping policies 52
7.3.5 Traffic policing policies 53
7.4 Resource Management operation 53
7.5 Resource Management approach 55
7.5.0 Overview 55
7.5.1 RM design and implementation 55
7.5.2 Simulation scenario and settings 56
7.5.3 Results 57
7.5.3.0 Overview 57
7.5.3.1 Adaptive DCC 57
7.5.3.2 Adaptive DCC with dynamic beta 58
7.5.4 Conclusion Resource Management approach 60

Annex A: Rationale for the limits imposed by congestion control 61

Annex B: Methods to characterize congestion control algorithms 62

B.1 Modelling of a rate control loop 62
B.1.1 Definition of the channel busy ratio limit 62
B.1.2 Function of the rate controller 63
B.1.3 Structure of a feedback controller 64

B.2 Control equilibrium 64

B.3 Stability 65
B.3.1 Different types of stability 65
B.3.2 Description of the controller by a differential equation 65
B.3.3 Convergence 65
B.3.4 Continuous-time stability 66
B.3.5 Discrete-time Stability 66

B.4 Control dynamics 66

Annex C: Characterization of congestion control algorithms 67

C.1 Reactive congestion control 67
C.1.1 Control equilibrium of the reactive congestion control 67
C.1.2 Convergence of the reactive congestion control 69
C.1.3 Stability of the reactive congestion control 70
C.1.3.1 Stability of the reactive congestion control without filtering according to ETSI TS 102 687 70
C.1.3.1.1 Continuous time stability 70
C.1.3.1.2 Discrete T_{off} stability and convergence speed 71
C.1.3.2 Stability of the reactive congestion control with filtering according to C2C-CC 73

C.2 Adaptive congestion control 74
C.2.1 Control equilibrium of the adaptive congestion control 74
C.2.2 Convergence of the adaptive congestion control 75
C.2.2.1 Continuous time behaviour of the adaptive congestion control 75
C.2.2.2 Stability of the discrete time adaptive congestion control 77
C.2.2.3 Convergence speed of the discrete time adaptive congestion control 79
C.2.2.4 Time behaviour of a discrete time adaptive congestion control implementation 83

C.3 Power control 85

Annex D: Channel load measurement 87

D.1 Channel load measurement overview 87

D.2 Influence of the channel load measurement on the reactive congestion control 87

D.3 Influence of the channel load measurement on the adaptive congestion control 90
D.3.1 CBR measurement with a fixed 100 ms measurement time interval 90
D.3.2 CBR measurement with a fixed 100 ms measurement time interval and a limited T_{off} range 93
D.3.3 CBR measurement and adaptive algorithm as specified in ETSI TS 102 687 95
D.3.4 Dynamic CBR measurement time and adaptive algorithm as specified in ETSI TS 102 687 97
D.3.5 Dynamic CBR measurement with enhanced filtering and adaptive algorithm as specified in ETSI TS 102 687 99

D.4 Influence of the MAC on the adaptive congestion control 101

Annex E: A real-time evaluation of basic resource management solution 105

E.1 Evaluation set-up 105

E.2 Results 105

Annex F: Maximum size of Facilities layer message size 107

History 108

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Foreword

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

Modal verbs terminology

In the present document "**should**", "**should not**", "**may**", "**need not**", "**will**", "**will not**", "**can**" and "**cannot**" are to be interpreted as described in clause 3.2 of the ETSI Drafting Rules (Verbal forms for the expression of provisions).

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Executive summary

The present document provide answers to several Resource Management questions and identifies several issues requiring additional studies with focus to those which are Radio Resource related. An overview of these answers and open questions are provided in this summary.

Based on the finding in the present document the focus of any RM operation should be on the single operational channel. Adjacent channel effects are mainly relevant when all operation channels are in a high load situation close to a congestion. A single channel RM will keep this effect at a minimum in the first place. Longer term envisaged high load conditions due to a high C-ITS penetration might require some adjacent channel RM optimizations. Nevertheless, the actual specification of single channel RM work should permit the inclusion of adjacent channel RM in the long-term development.

Two Decentralized Congestion Control (DCC) algorithms have been introduced in Release 1 as examples. Effectiveness and dynamic behavioural analyses in the present document show that these examples have drawbacks and need improvements.
The reactive DCC lacks effective use of radio channel resources and the channel utilization caused by each ITS-S is strongly dependent on the frame duration. Hence, the channel resources are not shared equally between the ITS-S. For these reasons, it is not recommended to use the reactive DCC for Release 2.

The adaptive DCC is more effective when it comes to the use of the channel resources, and the equal sharing of the channel resources is less dependent on the frame duration. Further optimizations are possible to improve the behaviour for a low number and a higher number of stations.
An improved DCC algorithm would converge within a few seconds to a steady state where all ITS-S are allowed to use equal portions of the available channel resources. In addition, this algorithm would offer the possibility to balance these resource portions based on frame priorities. I.e. the frame duration should not cause any unintended imbalance of the used channel resources.
Evaluations may be required for efficiently handling scenarios with heterogeneous service and station requirements.

The Channel Busy Ratio (CBR) measurement procedure as specified for Release 1 could be improved. This CBR determination causes heavy control loop oscillations of the channel load and needs major improvements. An obvious solution to this problem is a variable CBR measurement time that is equal to the packet transmission interval given by the DCC algorithm.

When using a proper working DCC for ITS-G5, the frame collision ratio can be significantly reduced when the Medium Access Control (MAC) Contention Window (CW) counter is increased. The value needs to be further analysed taking the aspect of additional transmission delay in account.

A technology agnostic resource management solution at the facilities layer and its interfaces to operational technology specific solutions at the lower layers is described. For new access layer technologies additional analyses will be required.

Based on the measurements performed by the access layer, the calculation of the available resources per each ALI group is performed at the facilities layer with technology specific operations, which will need to be defined.

How to distribute the available resources among the message services will need to be defined. The priority of each message service or message should be taken into account.

In Release 1 the networking and transport layer concept for traffic classes is used to map message priorities to access layer priorities. In Release 2, this concept should be extended considering forwarded data packets.

It is proposed that the RM include a table for each ALI, providing information on the resources consumed by the messages and the expected performance - for example, the achievable range - when that specific ALI is selected.

A separation between packet-centric multi-hop forwarding at the networking & transport layer and information-centric dissemination at the facilities layer is required for Release 2. Packet-centric forwarding should remain limited to safety-critical message services with strict latency constraints, while other message services rely on facilities layer mechanisms.

The data load created by multi-hop forwarding should be taken into account in the Release 2 Resource Management. The present document describes three approaches with different level of complexity and effectiveness.

The exchange of congestion-related information - in Release 1 realized through the Global CBR mechanism - should be maintained in Release 2, with potential refinements to the Release 1 aggregation logic.

Introduction

Cooperative Intelligent Transportation Systems (C-ITS) Release 1 standards have been developed from out of the perspective of static information dissemination in which the applications and message services have no knowledge of the transmission capabilities in the available radio channels.

As the number of the applications and message services at the facilities layer in Release 1 is limited, validations have shown that a predictable performance of these applications can be realized as long as there is a radio channel usage agreement among stakeholders that provides an acceptable system/radio channel(s) behaviour. This stable behaviour is reached by a combination of EU regulations, ITS Directive 2010/40/EU [i.31], C2C-CC Release 1 BSP profile [i.7] and the C-ROADs profile [i.8].

In Release 2 ITS services with a higher safety impact are being introduced. The introduction of these ITS services lead to significant higher Quality of Service (QoS) requirements. Since C-ITS data transmissions are mostly non-deterministic in time and size, the management capabilities of QoS in the network are limited. The ITS applications and message services are the only functionalities which are in possession of the relevant functional transmission requirements like size, timing and priority level of the information to be disseminated. Thus, further improvement of the QoS management should be handled by the applications and message services themselves by being aware of the underlying transmission capabilities (radio resources). Such knowledge enables the applications and message services to take appropriate measures in different communication situations.

As applications and message services are not aware of activities from other active applications and message services a general functionality which can keep track of all the applications and message services activities is required to allow resource allocation to take place. To allow any such general functionally to operate it is required that this functionality is also aware of all the available ITS-S lower layer capabilities and radio channel(s) occupation. This functionality should be technology agnostic to allow the use of different air interface technologies in the ITS band(s) e.g. (ITS-G5, C-V2X, RLAN, Mobile Radio, UWB [i.47]). This functionality should reside at the Facilities Layer (FL) and should manage the resources and capabilities among the applications and message services and therefore called Resource Management (RM).

Scope of the RM is to manage how the radio resources in a single or more channels are shared by the applications and message services. The term RM and not just radio resource management is justified by the need to distribute the radio resources among the applications and message services, which may involve functional decisions, and require the exchange of information among different layers of the ITS protocol stack. For the same reason, this term is preferred to the formerly used Multi-Channel Operation (MCO).

The present document evaluates possible RM approaches such that the most favourable version or versions can be derived in a future update of the present document. As a baseline, earlier results from the MCO study for ETSI TR 103 439 [i.1] Release 2 are used.

Any technology agnostic RM relies on proper information from lower layers about the dissemination possibilities and should ensure that no harmful interference can be caused by adjacent channel operation. The MCO study [i.1] showed that there are congestion requirements to comply with to avoid harmful interference effects like capacity, latency or range limitations.

The present document therefore also studies the related requirements which should be set for lower layers and how these should interface to higher layers. The maximization of technology agnostic parameter exchange between lower layers and the FL are also investigated. These parameters relate mostly to Congestion Control and its optimization.

Since Congestion Control handling at MAC/PHY layers can be handled differently for different radio access technologies, the present document presents general ITS-G5 DCC study results (ensuring technology neutrality). For more detailed adoption of other technologies then ITS-G5 further studies should be initiated.

The present document presents RM related recommendations and parameters technology agnostic. With respect to lower technology specific layer aspects only the ITS-G5 technology is addressed and therefore only the ITS-G5 related adjacent channel operations aspects, as identified in ETSI TR 103 439 [i.1] are considered. For the operation with other lower layer technologies such as LTE-V2X or NR-V2X further studies might be necessary. The access layer of ITS-G5 is assumed to be based on IEEE 802.11 [i.9], which includes the IEEE 802.11p and IEEE 802.11bd amendments.

There are several aspects to be investigated before a Resource Management solution can be defined. The present document addresses three specific aspects that need to be addressed for the definition of ITS resource management solutions:

1) the analyses of the Release 2 message services;

2) the identification of Congestion Control (CC) optimization possibilities; and

3) the identification of the adjacent channel interference management possibilities.

Other aspects such as CBR Management Method Selections and the selection of a CC Approach and Resource Management Process Selection will need to be considered to come to a full definition for a Release 2 RM specification, compatible with Release 1, but are not covered by the present document.

1 Scope

The present document identifies Resource Management (RM) at the Facilities Layer in relation to critical control requirements, capabilities, principles and parameters which could enable the definition of a mechanism supporting highly time and size dynamic data exchanging message services to operate robust, interoperable and backward compatible with existing ITS Release 1 and upcoming Release 2 message services in the 5,9 GHz ITS allocated band.

2 References

2.1 Normative references

Normative references are not applicable in the present document.

2.2 Informative 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 referenced document (including any amendments) applies.

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The following referenced documents may be useful in implementing an ETSI deliverable or add to the reader's understanding but are not required for conformance to the present document.

[i.1] ETSI TR 103 439: "Intelligent Transport Systems (ITS); Multi-Channel Operation Study; Release 2".

[i.2] ETSI TR 101 607: "Intelligent Transport Systems (ITS); Cooperative ITS (C-ITS); Release 1".

[i.3] ISO 26262-9:2018: "Road vehicles — Functional safety, "Part 9: Automotive safety integrity level (ASIL)-oriented and safety-oriented analyses".

[i.4] ETSI TR 103 903: "Intelligent Transport Systems (ITS); Framework; Basic principles; Release 2".

[i.5] ETSI TS 103 141: "Intelligent Transport Systems (ITS); Facilities layer function; Multi-Channel Operation (MCO) for Cooperative ITS (C-ITS); Release 2".

[i.6] ETSI TS 103 697: "Intelligent Transport Systems (ITS); Architecture; Multi-Channel Operation (MCO) for Cooperative ITS (C-ITS); Release 2".

[i.7] Car2Car Communication Consortium: "Basic System Profile (BSP)" - C2C-CC Profile Release 1.

[i.8] C-Roads profiles: "Release 2 of C-Roads Harmonised Communication Profile for C-ITS".

[i.9] IEEE 802.11™-2025: "IEEE Standard for Information Technology -- Telecommunications and Information Exchange Between Systems Local and Metropolitan Area Networks -- Specific Requirements - Part 11: Wireless Local Area Network (LAN) Medium Access Control (MAC) and Physical Layer (PHY) Specifications", April 2025.

[i.10] ETSI TS 103 836-4-1: "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; Release 2".

[i.11] ETSI TS 103 695: "Intelligent Transport Systems (ITS); Access layer specification in the 5 GHz frequency band; Multi-Channel Operation (MCO) for Cooperative ITS (C-ITS); Release 2".

[i.12] ETSI TR 101 612: "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".

[i.13] 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.14] ETSI TS 102 687 (V1.2.1): "Intelligent Transport Systems (ITS); Decentralized Congestion Control Mechanisms for Intelligent Transport Systems operating in the 5 GHz range; Access layer part".

[i.15] ETSI TS 103 175: "Intelligent Transport Systems (ITS); Cross Layer DCC Management Entity for operation in the ITS G5A and ITS G5B medium".

[i.16] ETSI EN 302 571: "Intelligent Transport Systems (ITS); Radiocommunications equipment operating in the 5 855 MHz to 5 925 MHz frequency band; Harmonised Standard covering the essential requirements of article 3.2 of Directive 2014/53/EU".

[i.17] V. Todisco, S. Bartoletti, C. Campolo, A. Molinaro, A. O. Berthet and A. Bazzi: "WiLabV2Xsim: Performance Analysis of Sidelink 5G-V2X Mode 2 Through an Open-Source Simulator", IEEE™ Access, vol. 9, pp. 145648-145661, 2021, doi: 10.1109/ACCESS.2021.3121151.

[i.18] Z. Wu, S. Bartoletti, V. Martinez, A. Bazzi: "A Methodology for Abstracting the Physical Layer of Direct V2X Communications Technologies", MDPI Sensors 2022, 22, 9330, doi: 10.3390/s22239330.

[i.19] G. Bansal, B. Cheng, A. Rostami, K. Sjoberg, J. B. Kenney and M. Gruteser: "Comparing LIMERIC and DCC approaches for VANET channel congestion control", 2014 IEEE™ 6th International Symposium on Wireless Vehicular Communications (WiVeC 2014), Vancouver, BC, Canada, 2014, pp. 1-7, doi: 10.1109/WIVEC.2014.6953217.

[i.20] M. Sepulcre, J. Mira, G. Thandavarayan, and J. Gozálvez: "Is Packet Dropping a Suitable Congestion Control Mechanism for Vehicular Networks?", 2020 IEEE™ 91st Vehicular Technology Conference (VTC2020-Spring), Antwerp, Belgium, 2020, pp. 1-5, doi: 10.1109/VTC2020-Spring48590.2020.9128822.

[i.21] G. Thandavarayan, M. Sepulcre, and J. Gozálvez: "Cooperative Perception for Connected and Automated Vehicles: Evaluation and Impact of Congestion Control", IEEE™ Access, vol. 8, pp. 197665-197683, October 2020, doi: 10.1109/ACCESS.2020.3035119.

[i.22] F. Marzouk, R. Zagrouba, A. Laouiti, and P. Mühlethaler: "An Empirical Study of Unfairness and Oscillation in ETSI DCC", 2015 International Conference on Performance Evaluation and Modeling in Wired and Wireless Networks (PEMWN'2015), November 2015.

[i.23] A. Bazzi: "Congestion Control Mechanisms in IEEE 802.11p™ and Sidelink C-V2X", 53rd Asilomar Conference on Signals, Systems, and Computers, Pacific Grove, CA, USA, 2019, pp. 1125-1130, doi: 10.1109/IEEECONF44664.2019.9048738.

[i.24] E. Xhoxhi and F. Schiegg: "Benefits of DCC Facilities in ITS-G5 Networks - First Simulated Results", IEEE™ 95th Vehicular Technology Conference: (VTC2022-Spring), Helsinki, Finland, 2022, pp. 1-7, doi: 10.1109/VTC2022-Spring54318.2022.9860904.

[i.25] G. Thandavarayan, M. Sepulcre, J. Gozálvez and B. Coll-Perales: "Scalable Cooperative Perception for Connected and Automated Driving", Elsevier Journal of Network and Computer Applications, vol. 216, pp. 103-655, May 2023, doi: 10.1016/j.jnca.2023.103655.

[i.26] A. H. Sakr: "Evaluation of Redundancy Mitigation Rules in V2X Networks for Enhanced Collective Perception Services", IEEE™ Access, vol. 12, pp. 137696-137711, 2024, doi: 10.1109/ACCESS.2024.3464514.

[i.27] Q. Delooz. A. Willecke, K. Garlichs, A.-C. Hagau, L Wolf and A. Vinel: "Analysis and Evaluation of Information Redundancy Mitigation for V2X Collective Perception", in IEEE™ Access, vol. 10, pp. 47076-47093, 2022, doi: 10.1109/ACCESS.2022.3170029.

[i.28] A. Figueiredo, P. Rito, M. Luís and S. Sargento: "Enhancing Vehicular Network Efficiency: The Impact of Object Data Inclusion in the Collective Perception Service", IEEE™ Open Journal of Intelligent Transportation Systems, vol. 5, pp. 454-468, 2024, doi: 10.1109/OJITS.2024.3437206.

[i.29] F. Schiegg et al.: "Automated Vehicle Marshalling: The First Functionally Safe V2X Service for Connected Automated Driving", IEEE™ Open Journal of Vehicular Technology, vol. 6, pp. 927-947, 2025, doi: 10.1109/OJVT.2025.3538698.

[i.30] G. Bansal and J. B. Kenney: "Achieving Weighted-Fairness in Message Rate-Based Congestion Control for DSRC Systems", 2013 IEEE™ 5th International Symposium on Wireless Vehicular Communications (WiVeC), Dresden, Germany, 2013, doi: 10.1109/wivec.2013.6698225.

[i.31] Directive 2010/40/EU of the European Parliament and of the Council of 7 July 2010 on the framework for the deployment of Intelligent Transport Systems in the field of road transport and for interfaces with other modes of transport.

[i.32] ETSI EN 303 797 (V2.1.1): "Intelligent Transport Systems (ITS); ITS-G5 Access layer in the 5 GHz frequency band; Release 2".

[i.33] C. Campolo, A. Molinaro and R. Scopigno: "Vehicular ad hoc Networks, Standards, Solutions, and Research", Springer, 2015, ISBN: 978-3-319-15496-1 (Print), 978-3-319-15497-8 (Ebook), doi: 10.1007/978-3-319-15497-83.

[i.34] Car2Car Communication Consortium: "Vehicle C-ITS Station Profile".

[i.35] D. Smely, S. Rührup, R. K. Schmidt, J. Kenney and K. Sjöberg: "Decentralized Congestion Control Techniques for VANETs". In: Campolo, C., Molinaro, A., Scopigno, R. (eds) Vehicular ad hoc Networks. Springer, Cham, 2015, doi: 10.1007/978-3-319-15497-8_6.

[i.36] R. K. Schmidt, T. Leinmüller and G. Schäfer: "Adapting the Wireless Carrier Sensing for VANETs", 6th International Workshop on Intelligent Transportation (WIT), Hamburg (2010).

[i.37] D. Eckhoff, N. Sofra and R. German: "A Performance Study of Cooperative Awareness in ETSI ITS G5 and IEEE WAVE", 10th Annual Conference on Wireless On-demand Network Systems and Services (WONS), 2013, doi: 10.1109/WONS.2013.6578347.

[i.38] Yongtae Park and Hyogon Kim: "Preventing congestion control oscillation in cellular vehicular communication", Electronic Letters, November 2021, Vol. 57, November 2024, doi: 10.1049/ell2.12319.

[i.39] SAE J2945/1: "Surface vehicle standard, On-board System Requirements for V2V Safety Communications".

[i.40] 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.41] ETSI EN 302 636-5-1: "Intelligent Transport Systems (ITS); Vehicular Communications; GeoNetworking; Part 5: Transport Protocols; Sub-part 1: Basic Transport Protocol".

[i.42] ETSI EN 302 636-6-1: "Intelligent Transport Systems (ITS); Vehicular Communications; GeoNetworking; Part 6: Internet Integration; Sub-part 1: Transmission of IPv6 Packets over GeoNetworking Protocols".

[i.43] T. Tielert, D. Jiang, Q. Chen, L. Delgrossi and H. Hartenstein: "Design Methodology and Evaluation of Rate Adaptation Based Congestion Control for Vehicle Safety Communications", 2011 IEEE™ Vehicular Networking Conference (VNC), Amsterdam, Netherlands, 2011, pp. 116-123, doi: 10.1109/VNC.2011.6117132.

[i.44] G. Bansal, J. B. Kenney and C. E. Rohrs: "LIMERIC: A Linear Adaptive Message Rate Algorithm for DSRC Congestion Control", in IEEE™ Transactions on Vehicular Technology, vol. 62, no. 9, pp. 4182-4197, November 2013, doi: 10.1109/TVT.2013.2275014.

[i.45] CAMP Vehicle Safety Communications 3: "Interoperability Issues of Vehicle-to-Vehicle Based Safety Systems Project", Phase 1 Final Report, April 2014.

[i.46] CAMP Vehicle Safety Communications 3: "Phase 2 Final Report Volume 1- Communications Scalability for V2V Safety Development" and "Phase 2 Final Report Volume 2- Communications Scalability for V2V Safety Analysis", February 2016.

[i.47] ETSI TR 103 970 (V2.1.1_0.11): "Intelligent Transport Systems (ITS); Feasibility study on the use of UWB; Release 2".

[i.48] IETF RFC 1042: "Standard for the transmission of IP datagrams over IEEE 802 networks".

3 Definition of terms, symbols and abbreviations

3.1 Terms

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

application: computer software program that performs a specific task directly for an user or one another application

automated system: computer (ICT) system that collects information and can react and perform tasks based on the data

NOTE: Automated systems are made using three entities:

- Sensors.
- Microprocessors.
- Actuators.

communication flows: data path to be followed by the information through an ITS from the source ITS-S to the sinking ITS-Ss

direct communication: message exchange between data sourcing ITS-Ss and data sinking ITS-Ss, without involvement of intermediary networking routing functions

NOTE: From a functional perspective, messages transported via Indirect Communication can be considered as Direct communicated when the messages cannot be processed (carried over in a secured envelope) along the indirect communication flow.

equivalent bandwidth: computed value coming from a computation of relevant statistical properties of the traffic source (e.g. Markov-modulated arrivals, moment generating functions, or large-deviation techniques), ensuring that the probability of exceeding resource limits remains below a defined threshold

NOTE: Equivalent bandwidth originates from wired networks and refers to the bandwidth that a given Message service effectively requires to meet its QoS constraints.

extra ITS: external ITS-S communication using a non-interoperable ITS, or interference from non-ITS sources, also inter ITS

heterogeneous: diverse in character or content

indirect communication: message exchange between data sourcing ITS-Ss and data sinking ITS-Ss, with the involvement of intermediary networking routing functions such as the Internet

intra ITS: internal ITS-S communication using interoperable ITS

ITS constellation: group of ITS-Ss which can exchange information

ITS-G5: ITS communication protocol based on IEEE 802.11 access layer

ITS service: service provided by an application to an end user or automated function

message service: Facilities Layer service which generates or processes data, triggered by an application or other message service, or a Facilities Layer service which executes system control functions for the purpose of correct operation of other message services or applications

3.2 Symbols

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

A	substitution constant
a	parameter of the channel busy ratio limit or substitution parameter
α	filter function factor
B	substitution constant
b	parameter of the channel busy ratio limit or substitution parameter
β	parameter of the adaptive rate control function
β_o	parameter of the adaptive rate control function
CBR	measured channel busy ratio
CBR_{ITS-S}	CBR input for the adaptive congestion control
CBR_{Limit}	upper limit of the channel busy ratio
CBR_{target}	parameter of the adaptive rate control function
$\mathrm{c_{fn}}$	control function
$\mathrm{c_{fn}}_a$	control function of adaptive congestion control
CL	channel load
$\widetilde{CL}$	equilibrium (i.e. steady state) channel load
$\widetilde{CL_a}$	equilibrium channel load of the adaptive congestion control
CL_a^-	channel load of the adaptive congestion control for the gain saturated case
CL_a	channel load produced by the adaptive congestion control
CL_a^+	channel load of the adaptive congestion control for the gain saturated case
$CL_{a\ envelope}$	envelope of channel load oscillations for the adaptive congestion control
CL_{af}	channel load of the adaptive congestion control with input filtering
CL_{as}	channel load of the adaptive congestion control for the gain saturated case
CL_m	measured channel busy ratio
CL_{max}	upper channel load limit
CR_{Limit}	upper channel occupation limit
Δt	duration of a time step
Δt_j	time step duration for network node j
δ_{max}	parameter of the adaptive congestion control
δ_{min}	parameter of the adaptive congestion control
Δu_{max}	variation of $u_{max}(t)$ within one time step
$\mathrm{f_{fn}}$	filter function
$\mathrm{f_{fn}}_a$	filter function of adaptive congestion control
G_{max}	gain saturation of adaptive congestion control
G_{max}^-	gain saturation parameter of adaptive congestion control
G_{max}^+	gain saturation parameter of adaptive congestion control
j	enumerator for network nodes
k	enumerator for network nodes and time steps
k_{offs}	offset coefficient
N	number of network nodes
n	number of steps
n_{bps}	number of useful bits carried by an Orthogonal Frequency Division Multiplexing (OFDM) symbol of an ITS-G5 transmission
n_c	number of steps to reach convergence
n_c^-	number of steps to reach convergence
n_c^+	number of steps to reach convergence
N_{byte}	number of bytes of the payload of an ITS-G5 frame
N_{est}	estimated number of network nodes
N_{sta}	number of ITS-Stations (I.e. network nodes) contributing to DCC
R	channel resources
r_g	target message rate of the adaptive congestion control
r_j	transmission rate of network node j
$\tilde{r}_j$	equilibrium rate of network node j
$\tilde{r}_{sj}$	equilibrium transmission rate of network node j for the gain saturated case of the adaptive congestion control
t	time

τ	duration of a time step, i.e. scaling factor for a limit transition
T_0	integration constant having a unit of time
t_0	integration constant having a unit of time
t_0^-	integration constant having a unit of time
t_0^+	integration constant having a unit of time
T_a	parameter for the control function of the reactive congestion control
T_b	parameter for the control function of the reactive congestion control
t_c	convergence time
t_h	duration of the transmission of the PLCP preamble and header of an ITS-G5 frame
t_n	time after *n* time steps
τ_n	time step size used for numeric solutions
t_{nj}	time after *n* time steps for network node *j*
T_{OFDM}	duration of an OFDM symbol of an ITS-G5 transmission
T_{off}	transmission idle time
$\tilde{T}_{off}$	equilibrium (i.e. steady state) transmission idle time
$T_{offLimit}$	upper transmission idle time limit
$T_{off\ max}$	upper T_{off} limit
$T_{off\ min}$	lower T_{off} limit
t_{offs}	offset coefficient
$T_{off\ total}$	total channel idle time observed during a measurement period
T_{on}	transmission duration
$T_{on\ max}$	upper transmission duration limit
$T_{on\ total}$	total channel active time observed during a measurement period
t_{pck}	duration of the transmission of an ITS-G5 frame
u	channel utilization
$\tilde{u}$	equilibrium channel utilization
u'	time derivative of u
u_a	channel utilization load of the adaptive congestion control
u_{aj}	channel utilization load of the adaptive congestion control for network node *j*
u_k	channel utilization of network node *k*
U_{max}	upper channel utilization limit
$u_{max}(t)$	dynamic upper channel utilization limit

3.3 Abbreviations

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

3GPP	3rd Generation Partnership Project
5G-NR	5th Generation New Radio
AC	Admission Control
AI	Artificial Intelligence
AIFS	Arbitration Inter-Frame
AL	Access Layer
ALI	Access Layer Instance
ASIL	Automation Safety Integrity Level
AVM	Automated Vehicle Marshalling
BE	Best Effort
BME	Bandwidth Management Entity
BTP	Basic Transport Protocol
C2C-CC	Car2Car Communication Consortium
CA	Cooperative Awareness
CAM	Cooperative Awareness Message
CAS	Cooperative Awareness Service
CBR	Channel Busy Ratio
CC	Congestion Control
CDF	Cumulative Distribution Function
C-ITS	Cooperative Intelligent Transportation Systems
CL	Channel Load
CP	Collective Perception

CPM	Collective Perception Message
CPS	Collective Perception Service
CSMA/CA	Carrier Sense Multiple Access with Collision Avoidance
CW	Contention Window
DCC	Decentralized Congestion Control
DEN	Decentralized Environmental Notification
DENM	Decentralized Environmental Notification Message
DENS	Decentralized Environmental Notification Service
DoS	Denial of Service
ECC	Electronic Communications Committee
EIRP	Effective Ideal Radiated Power
EU	European Union
FAC	Facility
FL	Facilities Layer
FL-SDU	Facilities Layer-Service Data Unit
FUSA	Functional Safety
GCRA	Generic Cell Rate Algorithm
GPC	GNSS Positioning Correction
I2V	Infrastructure to Vehicle
I2X	Infrastructure to Everything
ICT	Internet Communication Technology
ITS	Intelligent Transportation Systems
ITS-S	Intelligent Transportation Systems - Station
IVI	Infrastructure to Vehicle Information
IVIM	In Vehicle Information Message
LLC	Logical Link Control
LTE	Long-Term Evolution
MAC	Medium Access Control
MAP	Road topology
MAPEM	MAP (topology) Extended Message
MCM	Manoeuvre Coordination Message
MCO	Multi-Channel Operation
MCS	Modulation and Coding Scheme
MIM	Marshalling Infrastructure Message
MSDU	MAC Service Data Unit
MTU	Maximum Transmission Unit
MVM	Marshalling Vehicle Message
NR	New Radio
NTL	Networking & Transport Layer
OFDM	Orthogonal Frequency Division Multiplexing
PDCP	Packet Data Convergence Protocol
PER	Packet Error Rate
PHY	Physical layer
PLCP	Physical Layer Convergence Protocol
PRR	Packet Reception Ratio
QAM	Quadrature Amplitude Modulation
QM	Quality Management
QoS	Quality of Service
QPSK	Quadrature Phase Shift Keying
RLC	Radio Link Control
RM	Resource Management
RSSI	Received Signal-Strength Indicator
RSU	Roadside Unit
RTCM	Radio Technical Commission for Maritime services
RTCMEM	RTCM Extended Message
RWW	Roads Works Warning
SAM	Service Announcement Message
SDV	Slow Driving Vehicle
SHB	Single Hop Broadcast
SINR	Signal to Noise Interference Ratio
SNAP	Subnetwork Access Protocol
SP	System Profile

SPATEM	Signal Phase And Timing Extended Message
SREM	Signal Request Extended Message
SRTI	Safety Related Traffic Information
SSEM	Signal request Status Extended Message
TB	Transport Block
TC	Traffic Class
TDRC	Transmit Data-Rate Control
TLC	Traffic Light Control
TPC	Transmit Power Control
TR	Technical Report
TRC	Transmit Rate Control
TS	Technical Specification
UWB	Ultra Wide Band
V2V	Vehicle to Vehicle
V2X	Vehicle to Everything
VAM	Vulnerable road user Awareness Message
VoI	Value of Information
VRU	Vulnerable Road User
X2N2X	Anything to Network to Anything

4 Considerations

4.1 Introduction

The ITS Release 1 basic cooperative use cases, supported by the standards listed in ETSI TR 101 607 [i.2], are awareness oriented. When considered from an Automotive Safety Integrity Level (ASIL) perspective, according to ISO 26262-9 [i.3], ITS Release 1 supports some use cases of the Quality Management (QM) ASIL. For this level, there are no liability or other quality requirements defined, as identified in the ITS Framework Release 2 ETSI TR 103 903 [i.4].

The ITS Framework Release 2 (addressing both Cooperative-ITS (C-ITS) and non-C-ITS use cases), detailed in ETSI TR 103 903 [i.4], identifies specific Release 2 ITS services that are expected to support ASIL C and potentially ASIL D.

The support of higher ASIL levels results in additional and more stringent data quality and system performance requirements, including additional QoS requirements.

The present document focusses on two QoS related system improvement aspects:

1) how the ITS Service information dissemination could be better scheduled statistically; and

2) at the ITS-Station (ITS-S) system level, how the information dissemination could be better managed dynamically.

Both aspects are system aspects from which the first should be specified in System Profiles (SPs). For Release 1 the C2C-CC Profiles [i.7] and the C-Roads Profiles [i.8] have specified this to enable a predictable static message exchange behaviour. Both profiles refer to the ETSI standards listed in the ETSI TR 101 607 [i.2] for Release 1.

With regards to the second aspect, aspects related to the influence of ITS Services information exchange are identified in clause 4.2. Aspects related to the information dissemination QoS are clarified in clause 4.3. Finally, in clause 4.4, the system context is illustrated.

4.2 Message handling

Message handling is the static setting of C-ITS information exchange in a specific environmental context. As stated in clause 4.1, the C2C-CC and C-Roads profiles limit the Release 1 information dissemination to V2V, I2V message exchange in a single direct communication specific 10 MHz channel. C-Roads identifies other I2X/X2I direct communication into other channels for early C-Roads Release 2 within the same C-ITS Ecosystem (in EU regulated by the ITS directive [i.31]) to realize the required QoS.

In this context the C-Roads hybrid profile [i.8] (Internet based) is not considered at present as it does not provide dissemination QoS mechanisms for higher levels of safety and automation as expected for Release 2.

At present according to current Functional Safety Assessments (FUSAs), Internet information exchange does not provide sufficient QoS to be used for safety related information exchange to satisfy higher ASIL levels. As such related information exchange is not considered.

At the system level QoS is realized by means of stakeholder agreements and technical profiles such as the one from C2C-CC and C-Roads. As such they cannot be considered.

4.3 Quality of Service improvement

In Information and Communication Technology (ICT), QoS cannot be fully guaranteed. The main three areas, in which QoS mechanisms are realized:

1) From a functional perspective internet communication capabilities are business driven statistically estimated and adjusted ensuring a general level of QoS. Initially this was only statically realized and later extended to support exceptional (large) events such as a football game with over 50 000 spectators and based on related statistics. For instance, when there is a large sport event, additional equipment is temporarily installed. This can be seen as scenario management.

2) Internet protocol communication in general is handshaking based which allows the disseminating station to verify whether information is received. Direct communications are sensor networked (broadcast/unicast) based in which this verification cannot take place. QoS is reached by system agreements and resource assessment.

3) From a technical perspective information can for example be given different priorities or be offered different communication capabilities fitting to the information behaviour. This however always goes with a cost in which lower priorities will have to pay for the burden of the higher priorities.

In an open system such as the internet the large number of users (millions of users) damp the dynamic behaviour in general which has a positive effect on the QoS, by which the above three mechanisms are sufficient to realize an acceptable QoS for most internet services.

Information exchange in the domain of transport has additional requirements up on standard internet-oriented services. ITS related QoS, depending on the use case, has more stringent requirements related to latency, range, data rate, ranging accuracy, positioning accuracy, the number of participating devices, and to many other communication parameters. Depending on the transport use case, they often have a safety impact and therefore require higher levels of QoS. While some of the ITS Release 1 use cases can still be realized with an internet level of QoS, extended ITS Release 2 use case QoS requirements are more demanding.

One aspect of satisfying automated mobility systems is to provide higher levels of QoS to increase the reception probability so that information can be disseminated and reaches the users of that information in time. This presumes the accessibility of the network and that there is enough bandwidth available. Enough bandwidth is also reducing the sensitiveness to Denial-of Service (DoS, a typical cyber-attacks) attacks which make use of the bandwidth limitations of a network. Hence, only when common agreements in a closed communication environment are guaranteed, a high level of QoS can be reached.

In case of safety related services, specific levels of QoS are required as otherwise the safety related operation cannot be guaranteed. As QoS are coming with a price, discussions are started to what level of costs the safety should be guaranteed. This is a society cultural question and generally out of scope of standardization. However, C-ITS is of interest for a specific group of stakeholders and not to the society as a hole, which allowed the user to come to an agreement about the requirement levels for QoS.

For advanced C-ITS services and automated systems several approaches are being developed to realize a controlled system environment for extended trustworthiness and QoS needed for Release 2.

In the C-ITS ecosystem the message behaviour depends on mostly non-predictable events and circumstances. Within this ecosystem various parties are interested in different C-ITS services and make use of the communications capabilities in different ways. To realize a trustworthy communication behaviour, organizational agreements (regulations and/or requirements from consortia) for establishing a stable environment are required. As the C-ITS information dissemination is very dynamic in time and size, additional technical measures are needed to enable applications and message services to be aware of the communication capabilities and to allow them to take the appropriate measures in any traffic scenario. As a result, for C-ITS, but also for other message services, resource management methods will increase the dissemination trustworthiness. As this is a system related trustworthiness, each participating ITS-S needs to address the trustworthiness and QoS in a standardized manner as otherwise the predicted resulting behaviour of a group of ITS-S's cannot be trusted.

A basic trustworthiness and QoS improvement method is to increase the media (radio) access probability by e.g. increasing the communication bandwidth or by realizing agreements among the stakeholders on how to use the available media. This is useful for many of the non-safety or limited safety relevant message services.

As spectrum is a sparce resource, the available bandwidth for exchanging information is limited. For more critical safety requirements (ASILs C-D), this limitation can be an issue, and therefore more stringent measures are needed to realize a better QoS.

The way to realize an acceptable QoS depends on the network resources, they vary depending on the network configuration e.g. direct ITS-S to ITS-S (V2X) ITS-S - Service Provider - ITS-S (X2N2X) configurations (see ETSI TR 103 903 [i.4].

It could be that all stakeholders agree on what information should be disseminated. This is currently realized based on agreements (and associated profiles) between Car2Car Communication Consortium (C2C-CC) and C-Roads in Europe. This agreement comprises which Release 1 messages are at least disseminated in the single 10 MHz channel based on the IEEE 802.11p access layer technology, which is included in IEEE 802.11 [i.9]. This does not exclude that these messages can also be distributed via X2N2X networks, in parallel.

Practice has shown that for basic Safety Related Traffic Information (SRTI) information exchange both methods are useful.

When moving to more safety critical and automation Release 2 use cases, where more stringent QoS requirements are necessary, X2N2X QoS capabilities are expected not to grow with these needs, and direct data exchange between data source and data sink (ITS-S to ITS-S) without involvement of networks may therefore be the only possible solution for use cases with higher QoS needs.

The present document intends to introduce a method which further increases the QoS by making the applications and message services aware of the current dissemination capabilities of the access layer and whether they are influenced by other applications in the same ITS-S or in other ITS-S.

The present document therefore focuses on aspects which are relevant for the definition of a Resource Management (RM) method which supports an QoS improvement.

4.4 The system context

4.4.1 Overview

Previous work related to resource management was realized by the Multi-Channel Operation (MCO) work resulting in the MCO architecture for C-ITS as specified in ETSI TS 103 697 [i.6]. Present MCO functionalities are specified in the ETSI Release 2 standards, ETSI TS 103 141 [i.5], ETSI TS 103 836-4-1 [i.10] and ETSI TS 103 695 [i.11].

Figure 1 represents the MCO architecture as specified in ETSI TS 103 697 [i.6]. The RM has effect on the aspects of various layers, as clarified in the following clauses.

The MCO specifications focused on the realization of the multi-channel use. While the Resource Management (RM) extends and generalizes this concept also for use by single channel systems, focusing on increasing the QoS. The MCO architecture and related functionalities are therefore the basis for a wider resource management specification.

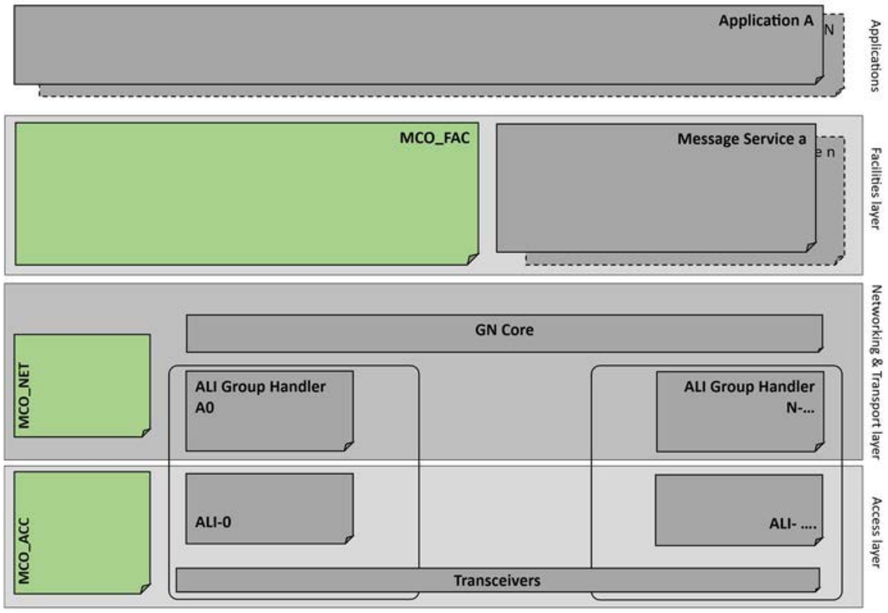


Figure 1: MCO Architecture (Source: ETSI TS 103 697 [i.6])

RM at the Facilities Layer (FL) is a functionality maintaining dynamic knowledge about the lower layer capabilities. It realizes higher levels of QoS by advising and directing applications about their message dissemination possibilities. This enables the applications to take appropriate functional and technical measures required for the use case or use cases it realizes. To allow the RM to fulfil its tasks, it communicates to the applications as well as to relevant lower layer functionalities as required. While the RM itself is technology agnostic, it can interface with technology specific entities at lower layers, although it expects technology agnostic parameter values. For the realization of the RM processes, RM related technology agnostic and technology specific functions can be expected at all layers. From a lower layer perspective, the RM is dependent on information about the Channel Load (CL), which is an aspect related to the Access Layer (AL) to be able to realize QoS improvements. In the following clause, relevant RM specific functional and technical aspects at different layers are recognized, and relevant studies are identified.

4.4.2 Channel load

The bandwidth of a radio channel is always limited, and it needs to be used efficiently. This means maximizing the data that can be exchanged in such channel. At the same time, overusing the channel may cause radio interference that is resulting in an increased reception error probability at the receivers. As a result, there is a maximum possible channel throughput and approaching it allows to optimally use the resources. How this is handled depends on the channel management principle that is used.

The specific split of radio resources, which can be in the frequency, time, space or code domain or a combination of these splitting principles, is technology specific.

In ITS-G5 based on IEEE 802.11 [i.9] technologies resources are split in the time domain with a listen-before-talk mechanism, whereas in LTE-V2X and 5G-NR-V2X sidelink there is a grid of time and frequency slots with synchronous access and scheduling procedures. In ITS Release 1, there are separate mechanisms identified for ITS-G5 and for LTE-V2X sidelink. For ITS-G5 the mechanism is specified in several ETSI specifications as identified in ETSI TR 101 607 [i.2] and for LTE-V2X sidelink by ETSI and 3GPP specifications.

In Release 2, an access layer technology agnostic solution at the higher layers needs to be defined to facilitate the use of various access layer technologies in the ITS spectrum bands. This implies the need to abstract the definition of used and available resources from the access layer to the layers above.

The measurement of the channel occupation and the evaluation of the available resources remain anyway technology dependent and is therefore performed in the access layer, defined separately per each technology.

When looking at the single channel and access technology, it is important to note that besides the inter ITS interference coming from ITS frames using the reference ITS access technology (ITS access technology used by the measuring ITS-S), extra ITS interference needs to be taken into account. When this external interference is above a given threshold it might also contribute to the channel load. Interference generated by a competing ITS technology can be also part of this extra (inter) ITS interference since it cannot be recognized by the receiver as useful signal. In the future, a differentiation between intra and extra ITS signal and interference might be required having in mind that ITS is operating in a shared radio environment.

4.4.3 Access layer operation

The AL is composed of the Medium Access Control (MAC) and Physical sub-layers. It handles the radio spectrum access for the transmission of frames. Higher layers can provide data packets to the access layer. The access layer decides whether to send frames, and when to transmit them by the mechanisms of the media access protocol.

With the aim to identify the occupation of the channel, in many systems including ITS-G5, the Channel Busy Ratio (CBR) is a metric derived from measurements which gather information about the load on the channel. This information can be provided to higher layers to inform them about the state of the channel from the local perspective of the ITS-S specific transceiver. The measurement performed locally can also be shared through higher layers with the neighbouring stations to improve awareness of channel use, as discussed in clause 4.4.5 in more detail. In Release 1, the CBR was directly related to a system CBR limit to control the amount of data that could be sent. The validity of such limit and the solutions defined in Release 1 to guarantee the respect of such limits are further elaborated in clause 5.

4.4.4 Adjacent channel

The MCO report ETSI TR 103 439 [i.1] presented the influence of operating information dissemination in adjacent channels and concluded that the traffic in one channel affects the resources available in the adjacent ones. The result also shows that the second adjacent channel can be neglected. This means that the maximum occupation allowed in one channel may affect the performance and thus the maximum occupation of the adjacent ones. These aspects are further investigated in clause 5.4.

4.4.5 Networking & transport layer operation

In Release 1, the Networking & Transport Layer (NTL) is realized by the GeoNetworking (GN) protocol as specified in ETSI EN 302 636-4-1 [i.40], complemented by the Basic Transport Protocol (BTP) as specified in ETSI EN 302 636-5-1 [i.41] and by the IPv6 over GeoNetworking Adaptation Sub-Layer (GN6ASL) as specified in ETSI EN 302 636-6-1 [i.42]. Together, these protocols provide the packet transport functions between ITS-S.

The GeoNetworking protocol provides geographical addressing, meaning that the destination of a packet is expressed in geographical terms such as a point or an area rather than by a conventional network address. When the addressed destination is within the direct radio coverage of the transmitting station, the packet is delivered by a single-hop transmission without any relaying. When the destination lies beyond direct radio range, intermediate stations may act as relays and apply the forwarding algorithms defined in ETSI EN 302 636-4-1 [i.40], resulting in multi-hop forwarding. The protocol maintains state information in the Location Table and manages packet handling according to the selected transmission mode. Its main tasks are:

- geographical addressing of packets for unicast, broadcast and anycast communications;
- single-hop transmission of packets when the destination is within direct radio coverage;
- multi-hop relaying of packets when the destination is outside the direct radio range of the source, using forwarding algorithms such as greedy forwarding and contention-based forwarding;
- maintenance of a Location Table (LocT) containing position vectors of neighbouring stations, extended by LocTEX-G5 fields when Decentralized Congestion Control (DCC) is active;
- exchange and storage of congestion-related information, namely local CBR measurements and CBR values received from neighbouring stations, which are combined to derive a Global CBR;
- provision of an interface to the transport protocols above and of link-layer addressing to the Access Layer below;
- handling of traffic classes to map facility layer service or message priorities to access layer priorities.

The Basic Transport Protocol (BTP) provides a lightweight, connection-less transport service between protocol entities of the FL. Its main purpose is the multiplexing and demultiplexing of messages from different facilities processes, such as CAM and DENM. BTP defines two header types, BTP-A for interactive packet transport and BTP-B for non-interactive packet transport. It resides above GeoNetworking in the protocol stack and operates in a similar way to UDP in the IP suite. BTP does not itself contribute to congestion estimation or resource allocation.

IPv6 integration is achieved through the GN6 Adaptation Sub-Layer (GN6ASL), which allows the transmission of IPv6 packets over GeoNetworking without modifications to IPv6. GN6ASL introduces the concept of geographical and topological virtual links in order to provide IPv6 with sub-IP multi-hop delivery and to extend connectivity towards infrastructure networks such as the Internet. The use of GN6ASL enables interoperability with IPv6-compliant systems but, like BTP, it does not have a direct role in Release 1 resource management.

In summary, the NTL in Release 1 ensures the geographical addressing of packets, supports single-hop transmission when possible, and provides multi-hop forwarding where needed. It also enables the dissemination of congestion-related information required for DCC. BTP and IPv6/GN6ASL complete the transport functions of the layer and are important for message delivery and Internet integration, but they are not directly involved in congestion control or resource management.

4.4.6 Applications, facilities layer and resource management

At the Facilities Layer (FL), the timely varying spectral resource capabilities come together with the timely changing functional requirements of applications and message services. As identified in the Multi-Channel Operation (MCO) concept study (ETSI TR 103 439 [i.1]), applications do not have any notion of the existence of other applications and their communication needs, therefore a Resource Management (RM) functionality at the FL (MCO management in ETSI TR 103 439 [i.1]) intends to facilitate a more predictable use of the actual radio resources.

As RM takes care of the radio resource management in general, it is proposed to rename the MCO FL functionality as defined in ETSI TR 103 439 [i.1], into a more general RM for all kind of configurations (i.e. single-channel and multi-channel configurations).

The RM is a FL functionality which replaces what is currently specified as the MCO-Facilities (MCO-FAC) in ETSI TS 103 141 [i.5].

The RM operation depends on the capabilities of the lower layers and on the proper operation of the applications and the message generating and manipulating message services. To allow the RM to provide robust operation of applications and message services, it is necessary that all dataflow functionalities at all layers, from applications to AL functionalities, operate with similar trustworthiness and QoS.

In clause 5, relevant lower layer robustness improvements are depicted; in clause 6, the application and message service parameters and possibilities are considered; and in clause 7, the functional layer mechanisms are investigated and considered.

5 Decentralized Congestion Control optimization

5.1 Introduction

In Release 1, congestion control is managed separately for different Access Layer Instance (ALI) groups. The extended concept as outlined in the present document is based on the analysis of the ITS-G5 AL technology, but it is not limited to this specific AL technology. However, to use the concept with other technologies, additional studies might be needed.

Clause 5 focusses on Decentralized Congestion Control (DCC) in a single channel. It contains a review of the related standards of Release 1 and identifies the aspects where Release 2 can benefit from modifications to comply with the MCO framework.

5.2 Decentralized congestion control in Release 1

5.2.1 Introduction

This clause provides a synthetic review of DCC as it is defined in Release 1.

First, it recalls the definition of the main metrics used for congestion control. Then details the limits that apply and the constrains imposed to the congestion control algorithm.

The congestion control algorithm to be used is not specified by the standards but needs to respect the given constraints.

5.2.2 Overview of Release 1 DCC

The general description of Release 1 DCC is provided in ETSI TS 103 175 [i.15], which details the entities at the various layers of the C-ITS protocol stack. In Release 1, DCC has entities at the access layer, detailed in ETSI TS 102 687 [i.14], and at the networking & transport layer, detailed in ETSI TS 102 636-4-2 [i.13].

5.2.3 Metrics

DCC is based on the concept of Channel Busy Ratio (CBR), as defined in ETSI EN 302 571 [i.16], which determines the level of load of the channel. More specifically, the receiver determines every T_{CBR}, set to 100 ms, the time when the strength of the received signal exceeds -85 dBm, called T_{busy}. The CBR is calculated every T_{CBR} as:

$$CBR = \frac{T_{busy}}{T_{CBR}} \qquad (1)$$

NOTE: It is common use to consider the own transmission time as part of T_{busy} as specified in IEEE 802.11 [i.9], even if this is not explicitly mentioned in the current specifications.

The measured CBR can be elaborated at the networking & transport layer and exchanged with the neighbouring nodes up to the second hop. This allows, as detailed in ETSI TS 102 636-4-2 [i.13], to obtain average values of the CBR in a larger area than the one directly observed by the station. This aspect is further discussed in clause 5.2.6.

Other metrics that are relevant for the DCC process are:

- The duration of a single transmission, denoted as T_{on}.
- The time between the end of a transmission and the beginning of the following one, denoted as T_{off}.
- The portion of time within a reference interval (set to 1 second) when the station is transmitting in the given channel, called *duty cycle*.

5.2.4 Limit imposed to the channel load

The limit for the channel load of each station is indicated in the ETSI EN 302 571 [i.16], which in turn is based on ETSI TS 103 175 [i.15] and ETSI TR 101 612 [i.12]. The limit provides a minimum time between two consecutive transmissions where the transceiver is not allowed to generate a signal (minimum T_{off}, as defined in clause 5.2.3), based on the duration of the last transmission (T_{on}, as defined in clause 5.2.3) and the measured CBR.

For any value of the CBR, T_{off} needs to be larger than 25 ms. If the CBR is equal or above to 0,62, the T_{off} needs also to comply with equation (2):

$$T_{off} \geq \min\left\{1\,000, T_{on} \times \left(4\,000 \times \frac{CBR-0{,}62}{CBR} - 1\right)\right\} \qquad (2)$$

with T_{off} expressed in milliseconds. The rationale behind the equation above is discussed in Annex A.

In addition, ETSI EN 302 571 [i.16] indicates a maximum T_{on} of 4 ms and a maximum duty cycle of 3 %.

5.2.5 Release 1 DCC at the access layer and constraints to the algorithm

ETSI TS 102 687 [i.14] details the constraints for the algorithm to be implemented at the access layer. The specific algorithm is not defined but left to the implementer. The constraints are as follows:

- The algorithm runs on each frequency channel specified in ETSI EN 302 571 [i.16] independently.
- The algorithm runs in an infinite loop.
- The algorithm is activated at least every 200 ms.
- The algorithm does not exceed the limits discussed in clause 5.2.4.

In the same document, two possible classes and an example for each of them are reported.

The first class is called reactive and consists in the use of a number of states. The reactive DCC algorithm transits from one state to another based on the measured CBR; the state defines the value of the minimum T_{off}. The minimum T_{off} that follows from each state can be dependent on T_{on} (for example, two different values can be defined if the packet is small or large). ETSI TS 102 687 [i.14] does not specify the number of states or the values to be used per each state, but gives an example in its Annex A. In the reactive approach, at each step the station measures the CBR, identifies the state, and sets the minimum T_{off} accordingly. The minimum T_{off} has thus a granularity that is defined by the number of states and the associated values.

The second class is called adaptive and increases or reduces the minimum T_{off} based on the measured CBR. In this case, ETSI TS 102 687 [i.14] specifies the calculations that need to be performed from the measured CBR to the minimum T_{off}, also including the values of the several parameters used by the calculations. ETSI TS 102 687 [i.14] also describes, in its Annex B, a possible implementation of the "gate keeping" function at the interface to the networking & transport layer to cope with messages of variable size.

5.2.6 Release 1 DCC at the networking & transport layer

ETSI TS 102 636-4-2 [i.13] describes the media-dependent functionalities for ITS-G5 at the networking & transport layer, also called DCC_NET. If GeoNetworking is implemented, DCC_NET is mandatory. If it is implemented:

- It maintains a number of DCC state variables (CBR_L_0_Hop, CBR_L_1_Hop, CBR_L_2_Hop, CBR_R_0_Hop, CBR_R_1_Hop, CBR_G, and CBR_Target), also using the Location Table Entry Extension for ITS-G5 (LocTEX-G5); LocTEX-G5 is an extension of the location table of the GeoAdhoc router.
- It periodically calculates the global Channel Busy Ratio, CBR_G.
- It processes and provides DCC-related information from/to DCC_CROSS.
- It transmits and receives DCC-related information to other GeoNetworking routers using the extensions for GeoNetworking packet handling.
- It optionally sets the transmission power limits, as specified in ETSI TS 103 175 [i.15], clause 6.2.

Regarding the state variables CBR_L_0_Hop, CBR_L_1_Hop, and CBR_L_2_Hop, they are the CBR measured by the station (0 to indicate no hops), the CBR received by its neighbours (1 hop), and the CBR that its neighbours have forwarded as they have in turn received from them their neighbours (2 hops), respectively. CBR_L_1_Hop and CBR_L_2_Hop are conservative values derived from the possibly several CBR values received from the neighbours, with the specific calculations described in ETSI TS 102 636-4-2 [i.13], clause 5.3.

CBR_R_0_Hop and CBR_R_1_Hop are the measured CBR shared by the station and the received CBR shared by the station, calculated as an average of those received from the neighbours.

Per each received packet, each station stores the CBR_R_0_Hop and CBR_R_1_Hop received from all the neighbours in the LocTEX-G5, together with information about transmit power and Received Signal-Strength Indicator RSSI.

Each station then calculates the *global CBR* CBR_G based on CBR_L_0_Hop, CBR_L_1_Hop, and CBR_L_2_Hop, which are in turn evaluated as a function of all received CBR_R_0_Hop and CBR_R_1_Hop. CBR_G is conservatively calculated, as detailed in ETSI TS 102 636-4-2 [i.13], clause 5.3. These calculations are performed every 100 ms.

CBR_Target is finally the value used by DCC as target, which needs to be the same as the one used at the access layer; currently, it is set to 0,62. The value of CBR_Target is used during the calculation of CBR_G.

5.2.7 Release 1 DCC at the facilities layer

The overall DCC architecture detailed in ETSI TS 103 175 [i.15], includes at the facilities layer a DCC_FAC function. However, DCC_FAC was not eventually defined in Release 1.

5.3 Critical analysis of Release 1 DCC

5.3.1 Introduction

The main aspects that could be revised in Release 2 are analysed in this clause.

5.3.2 Analysis of global CBR sharing

Release 1 extends local congestion sensing by introducing the concept of the global Channel Busy Ratio (CBR_G) (see clause 5.2.6). CBR_G is formed by combining an ITS-S's own CBR measurement with CBR values received from neighbouring stations via 1-hop and 2-hop piggybacking. The intended effect is to extend awareness beyond the immediate carrier-sense range, allowing nodes that do not sense local congestion to still contribute to congestion control efforts. This mechanism addresses known challenges in vehicular environments, such as hidden nodes, asymmetric sensing ranges, and local fading, which can make purely local decisions inadequate for achieving both local and global fairness e.g. as presented in the publication "Decentralized Congestion Control Techniques for VANETs" [i.35].

The concept was investigated in the CAMP V2V-Interoperability project [i.45], [i.46], where the LIMERIC algorithm [i.44] was tested with local, one-hop, and two-hop CBR sharing based on PULSAR [i.43]. LIMERIC remains stable in all cases, but the degree of *spatial fairness* improves with broader information sharing. Without sharing, nodes react only to their own CBR, achieving fairness locally. Sharing one-hop or two-hop values allows nodes to account for the interference they cause elsewhere, improving fairness - particularly with two-hop sharing, which approximates the interference range. Experimental results from the CAMP project [i.45], [i.46] showed that using the maximum CBR observed within two hops prevented spatial oscillations and unfair channel use seen in dense deployments. However, sharing also introduces delay, as received CBR values may refer to previous intervals. To preserve stability, the adaptive gains in LIMERIC were reduced, with a minor impact on convergence speed.

In Release 1, CBR_G is computed by selecting either the maximum or the second-highest value from local, 1-hop, and 2-hop CBR reports within a validity window (T_Cbr) [i.13]. This approach is designed to be conservative, emphasizing the highest occupancy observed across the various reports. Consequently, the final CBR_G value may be influenced by a single, anomalous high report from the 1- or 2-hop data, even when the local channel does not exhibit signs of congestion.

While sharing of global CBR is specified in in the ITS-G5 extensions of GeoNetworking [i.13] including corresponding header fields and location table entries, to date, the global CBR has not been adopted in the system profiles from C2C-CC [i.7] and C-Roads [i.8]. As a consequence, practical implementation of the global CBR has been limited, both in research prototypes and commercial implementations. Existing implementations either do not populate these fields or ignore them. Specifically, both the C2C-CC Basic System Profile [i.7] and the C-Roads Harmonized Profile [i.8] rely on local CBR measurement for congestion control.

5.3.3 Analysis of the limit

When looking at the single generic channel, the limit imposed in Release 1 implies restrictions when the CBR exceeds 0,62. This number, which was chosen having a few message services and relatively small messages in mind, appears lower than the maximum channel load tolerated in ITS-G5. It appears therefore reasonable to verify if such value is still a good choice or it should be revised once moving to Release 2. It can be noted that an increase of the limit would mean that the already enrolled devices still comply, while a reduction of the limit would need to include exceptions for the devices implemented following the specifications in Release 1.

With the aim to investigate this aspect, a simulation campaign was performed using the open-source WiLabV2Xsim [i.17]. Selected results are shown hereafter assuming a variable number of cars distributed on a highway segment of 8 km with 3 lanes per direction. The simulations are intended to obtain general considerations without focusing on a specific message service; for this reason, each vehicle is assumed to transmit 10 packets per second, and all packets are of the same size; different values for the packet size are assumed in different simulations. In particular, 350, 550, and 1 000 bytes are considered, where the first value is a reasonable reference for Release 1 messages and the last one for larger Release 2 messages. These three values correspond to a duty cycle of approximately 0,58 %, 0,84 %, or 1,44 %.

ITS-G5 nodes are assumed to transmit at 23 dBm Effective Isotropic Radiated Power (EIRP), with 3 dBi antenna gain at the receiver, and 6 dB receiver noise figure. The access category Best Effort (BE) is adopted, corresponding to Arbitration Inter-Frame Spacing (AIFS) equal to 110 µs, Contention Window (CW) equal to 15. The sensing threshold, when a preamble is detected, is set to -85 dBm, whereas it is set to -65 dBm otherwise. The modulation and coding scheme corresponding to Quadrature Phase Shift Keying (QPSK) and 1/2 coding rate is assumed. The modified Electronic Communications Committee (ECC) rural model from ETSI TR 103 439 [i.1] is used for the propagation, with correlated shadowing with standard deviation 3 dB. The model implies a loss exponent of 2 up to 128 m, then 2,8 up to 512 m, and 3,3 m above 512 m.

To evaluate the correctness of the decoding of each received signal, the average Signal to Noise and Interference Ratio (SINR) is calculated, where both noise and interference are assumed Gaussian and White. The reception is identified as correct when the SINR is above a given threshold as elaborated in "Methodology for Abstracting the Physical Layer of Direct V2X Communications Technologies" [i.18] Following the approach detailed in the same reference, the threshold is set to 1,2, 1,9, and 2,4, for 350, 550, and 1 000 bytes, respectively.

Results are provided in terms of measured CBR, Packet Reception Ratio (PRR) and Packet Error Ratio (PER). The PRR is obtained dividing the number of correctly decoded packets to the number of packets attempted to be decoded. The PER is the complementary value, i.e. the number of packets not correctly decoded divided by the number of packets attempted to be decoded.

Figure 2 represents the CBR varying the density and with different packet size. More specifically, it shows the median (i.e. the 50th percentile) of the distribution of the CBR measured in each interval by each station. As expected, the CBR increases almost linearly for low densities where collisions are limited and then slower when collisions become frequent. In addition, as expected, the increase is faster with larger packets. What is instead less obvious and therefore relevant to remark is that slower increase in CBR occurs at larger CBR values when the packets are larger; this effect is due to the lower relative impact of the inter-frame spaces when the packets are larger.

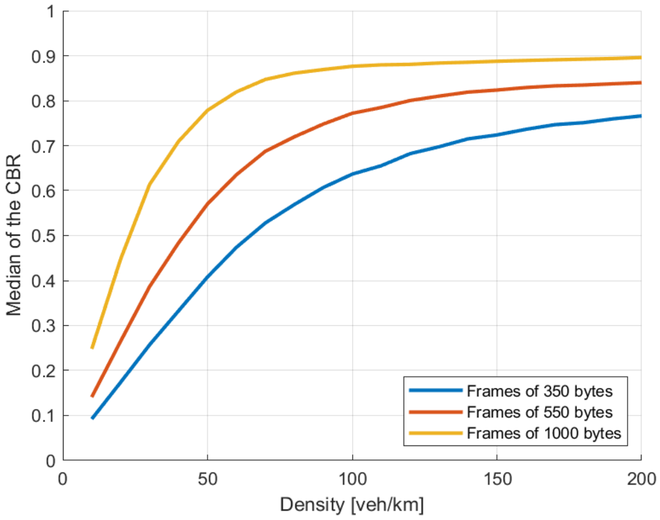


Figure 2: Median of the CBR varying the density

In Figure 3, the median CBR is shown in the x-axis and the PRR is plotted in the y-axis, when implicitly varying the density. Specifically, the PRR is calculated as an average at a distance of 400 m between transmitter and receiver. These results further show that the maximum CBR that can be tolerated changes when different packet size is assumed, with a higher CBR corresponding to a larger packet if the same PRR is assumed. This means that the larger packets expected in Release 2 may allow to increase the limit for congestion control. However, the increase appears limited.

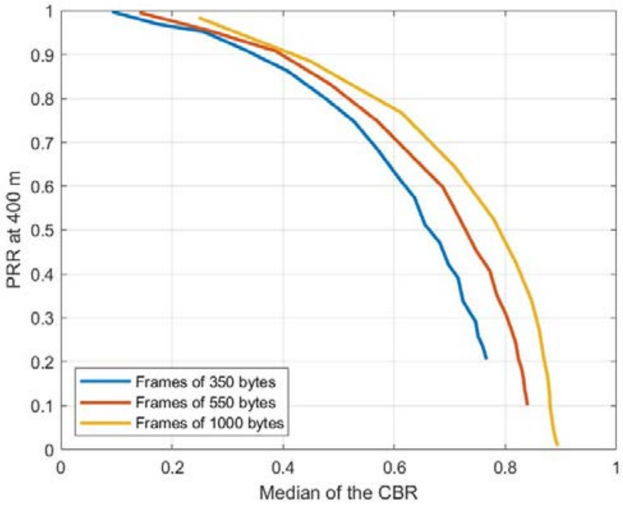


Figure 3: Average PRR at 400 m varying the median CBR

In Figure 4, the median CBR and a measure of the average number of messages that are correctly decoded at 400 m per km and per second are shown varying the average messages sent per km and per second. Also in this case, the results are obtained by implicitly varying the vehicle density. Looking at the blue curves, corresponding to the median CBR, it can be noted that trends are consistent to those shown with the density in the x-axis in Figure 2; indeed, since 10 packets per second are sent by each vehicle, the average sent messages per km and second is proportional to the density. Looking at the red curves, which more specifically shows the product between the average number of messages sent per km per second and the PRR at 400 m, it can be noted that they increase for small values of the sent packets (i.e. for low vehicle density) and then decrease after a maximum is reached. In each of the three red curves, a star is added when the median CBR corresponds to 0,62; as observable, the marked values are close to the maximum of the curves, meaning that a load on the channel higher than the limit imply an excessive increase in the collision probability.

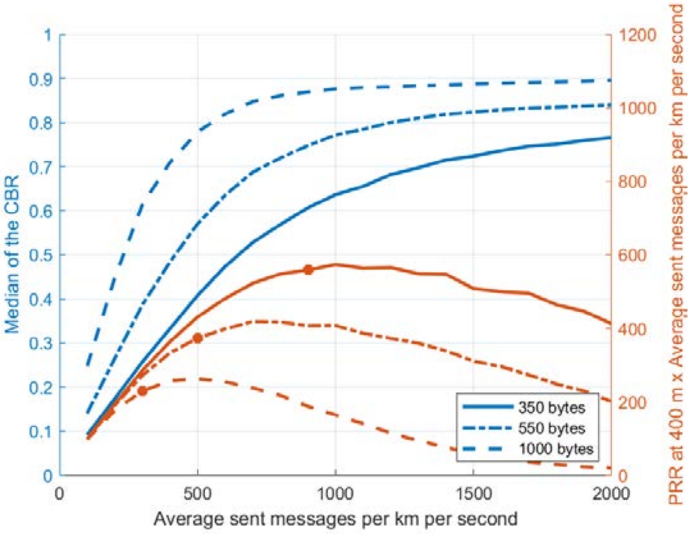


Figure 4: Median CBR and measure of the average number of messages correctly received at 400 m per km per second

Finally, in Figure 5, the PER at 400 m is shown together with the CBR varying the average messages sent per km and per second. Looking at the PER, it increases with larger packets, both due to a higher occupation of the channel and a higher SINR required to correctly decode the packet. Also in this case, the values corresponding to a median CBR equal to 0,62 are marked with a star, showing that the PER at 400 m is between 0,2 and 0,4 when the channel occupation is close to the limit imposed by current specifications. By looking jointly at Figure 4 and Figure 5, it can be noted that the maximum average number of correctly decoded messages at 400 m is achieved close to the channel occupation limit, despite the PER is larger than 0,2.

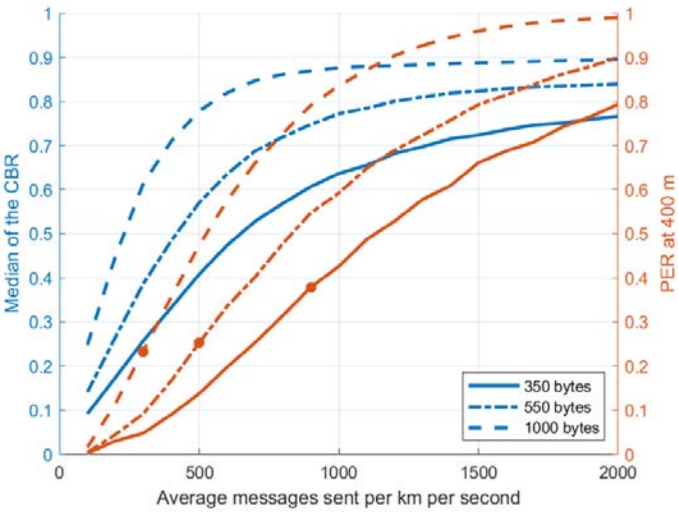


Figure 5: Median CBR and frame error probability at 400 m, varying the messages sent per km per second

The overall conclusion is that, when assuming that the packets are all of the same size, a different packet size could lead to a different maximum congestion threshold. Similar considerations apply also to other cases, such as if the packets are all with the same priority, but the priority is varied, because of different durations of the inter-frame spaces; or if the reference distance is changed. This means that it is not possible to determine a specific number for the optimum limit, instead this optimum depends on a large number of parameters which may change in time and space and are additionally depending on the use case.

These results are consistent with what was discussed in the reference literature and with following main deriving observations:

- A specific optimum value does not appear to be possible to derive, as it depends on a very large number of factors, which can also depend on the application and vary in time and space.
- The threshold 0,62 as given currently in the standards appears reasonable also for Release 2.
- A mechanism allowing a centralized authority to update the limit when deemed necessary could be introduced. The frequency of this kind of updates may be in the order of months or years and should introduce small variations based on considerations derived from the real implementations. The mechanism should be defined considering fairness between vehicles that may have temporarily different values during the update; this may be granted by only allowing small variations but needs further analysis. As an example, the parameter updates, when necessary, could be distributed along with the certificates.

5.3.4 Analysis of algorithms

The current limits imposed to the algorithm that an implementation can use may not be sufficient. The current limits imposed by the standard ETSI TS 102 687 [i.14], in fact, do not guarantee fairness and may cause different implementations to have different levels of access to the channel in congested situations.

With the objective to elaborate on this statement, hereafter some results are shown using the same simulator and settings of clause 5.3.2, adding the reactive and adaptive approaches described in ETSI TS 102 687 [i.14], without GeoNetworking. These results are not meant to comprehensively compare specific solutions, for which the reader can refer to the following references [i.19], [i.20], [i.21] and [i.22], but only to remark the different impact that different algorithms can have.

In particular, hereafter either 200 vehicles per km are assumed to transmit messages of 350 bytes (scenario A), or 100 vehicles per km are assumed to transmit messages of 1 000 bytes (scenario B). These settings allow to investigate a scenario where the channel is slightly overloaded if no congestion control is implemented. Each vehicle generates one packet every T_{on}+T_{off}, where T_{off} is set by the congestion control algorithm, based on the measured CBR. A new packet is generated at least every 1 second and at most every 100 ms. Each vehicle generates one packet every 100 ms if DCC is not active.

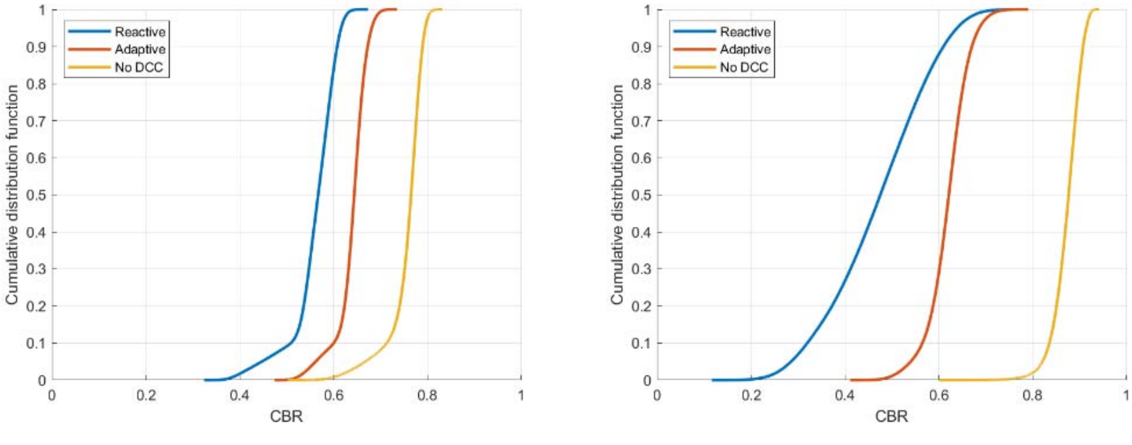
When the reactive approach is used, the profile defined by the C2C-CC in the Vehicle C-ITS station profile, Release 1.6.7 is used. The profile requires that the CBR is updated making an average of the last measured CBR and the one calculated in the previous measurement interval. The profile also sets the values of the minimum T_{off} for CAM messages to those of Table A.2 in ETSI TS 102 687 [i.14], which are therefore used for the 350 bytes packets; consistently, for the 1 000 bytes packets those of Table A.1 in ETSI TS 102 687 [i.14] are used. These values are also reported in Table 1.

Table 1: Settings of reactive DCC

State	CBR	Minimum T_{off} with packets of 350 bytes	Minimum T_{off} with packets of 1 000 bytes
Relaxed	< 30 %	50 ms	100 ms
Active 1	30 % to 39,99 %	100 ms	200 ms
Active 2	40 % to 49,99 %	200 ms	400 ms
Active 3	50 % to 65 %	250 ms	500 ms
Restrictive	> 65 %	1 000 ms	1 000 ms

When the adaptive approach is used, the settings defined in ETSI TS 102 687 [i.14] are used.

Figure 6 and Figure 7 refer to scenarios where all the vehicles implement the same algorithm, reactive or adaptive, or do not implement any algorithm. Figure 6, in particular, shows the Cumulative Distribution Function (CDF) of the CBR measured by every vehicle in every measurement interval T_{CBR}. The two subfigures refer to the two scenarios. The yellow curve, referring to no DCC implemented, provides a reference in the case all vehicles transmit exactly 10 packets per second. What can be observed is that both the reactive and the adaptive approaches reduce the measured CBR, which remains in most of the cases below or slightly above 0,6 as required by the limit imposed. The reactive approach implies a lower CBR than the adaptive approach, meaning that it reduces the average packet generation frequency stronger than the adaptive approach. A last observation that appears relevant is that in most of the cases the CDF tends to remain around a small range of the CBR; this is consistent with the stationarity of the scenarios and means that the algorithm tends to reach an equilibrium at a certain T_{on}+T_{off}. However, in Scenario B, where the channel is more congested, the CDF related to the reactive approach spans over a larger range of values of the CBR, which suggests that the algorithm does not converge to an equilibrium.

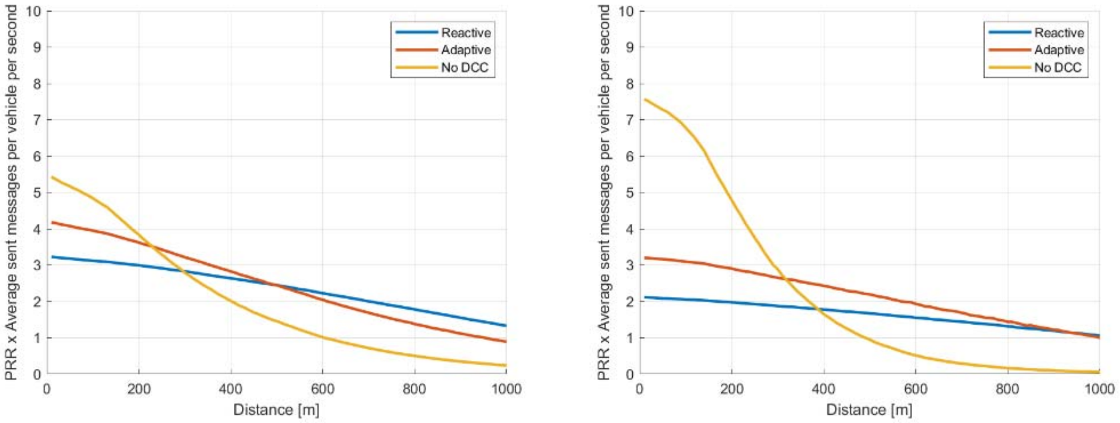


(a) 200 vehicles per km, 350 bytes

(b) 100 vehicles per km, 1 000 bytes

Figure 6: Cumulative distribution function of the measured CBR

The impact on the quality of the communication is shown in Figure 7, where the PRR multiplied by the average messages sent per vehicle per second is shown varying the transmitter-receiver distance. The metric observed corresponds to the average number of packets that can be correctly decoded by a receiver at the given distance and makes the performance of the various cases comparable, even if the number of generated packets is not the same. As observable, in both scenarios, when no DCC is implemented, the communication becomes unreliable at a shorter distance compared to the other cases. For example, looking at scenario a (Figure 7(a)), only one average packet can be correctly decoded at 600 m if there is no DCC, whereas more than two can be correctly decoded if a DCC algorithm is implemented. Comparing the two algorithms, the adaptive approach appears to provide a slightly higher number of correctly decoded packets, at least up to a certain distance. Overall, a higher transmission rate privileges the reception at shorter distance, whereas a lower transmission rate does the opposite.

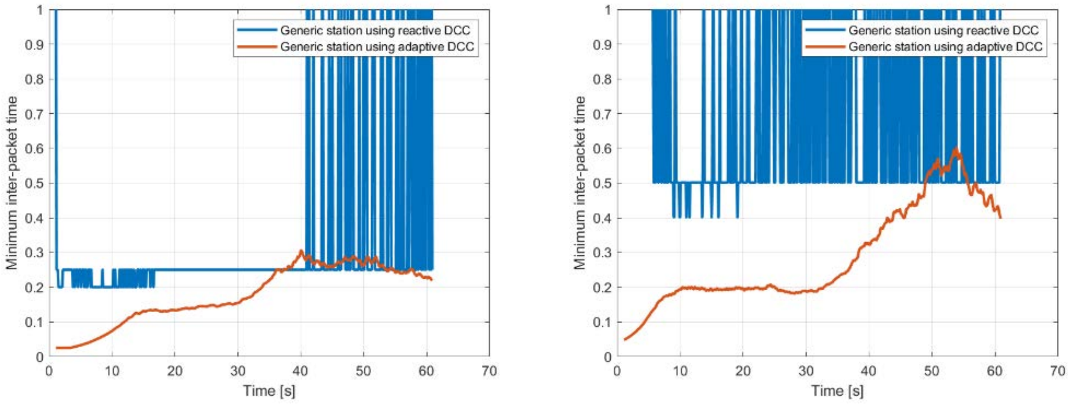


(a) 200 vehicles per km, 350 bytes (b) 100 vehicles per km, 1 000 bytes

Figure 7: Average number of messages per second correctly received from a station at a given distance

The results shown above suggest that the adaptive approach is able to maintain the channel occupation closer to the limit imposed, with a more stable value of the selected T_{on}+T_{off} and with slightly higher number of correctly decoded packets at short-to-medium distances. However, the difference between adaptive and reactive may not appear significant.

In order to verify what happens if not all the vehicles implement the same algorithm, Figure 8 refers to a case where 50 % of the vehicles implement the reactive approach and the remaining 50 % implement the adaptive approach. In Figure 8, in particular, the minimum inter-packet time (i.e. T_{on}+T_{off}) of two stations are shown varying the simulation time. The two stations are randomly selected, one among those implementing the reactive approach and the other among those implementing the adaptive approach. What can be observed is that the two stations have significantly different values of the minimum inter-packet time; the reactive approach, in particular, tends to use a larger gap, which means a lower frequency of packets sent. Having stations that generate packets at different frequencies because they are using different algorithms appears as a possible issue.



(a) 200 vehicles per km, 350 bytes (b) 100 vehicles per km, 1 000 bytes

Figure 8: Variation of the minimum inter-packet generation interval for randomly selected stations varying time

The results shown are consistent with what has been discussed in the literature. The following observations can be made:

- The specific algorithm that is adopted impacts on the system performance. The algorithm acts on the trade-off between the number of packets sent and the probability of collisions; reducing the packets sent may reduce the information available at shorter distance but increase that available at longer distance. This means that the distance from the limit at which the congestion control algorithm works has a significant impact on the system.

- To comply with the limit described in clause 5.2.4 may not be sufficient to guarantee a certain performance and fairness among stations. Different algorithms may imply, in fact, that different amount of information is available at the receivers, which means that the principle of fair access to the channel may not be guaranteed. A solution may be to have a single algorithm or at least stricter rules for the definition of the algorithm.
- The congestion control algorithm should (i) imply small variations of available resources when there are small variations of CBR, and (ii) allow the channel use to remain close to the maximum in congested conditions. For these reasons and given the detailed analysis in this clause and in the annexes, the use of the reactive algorithm as described in ETSI TS 102 687 [i.14] is not recommended.

5.3.5 Analysis of variables that impact congestion control

Different options to cope with congested situations are suggested in Release 1 specifications, including Transmit Power Control (TPC), Transmit Rate Control (TRC), and Transmit Data-Rate Control (TDRC). For more details see the references [i.20], [i.23], and [i.24].

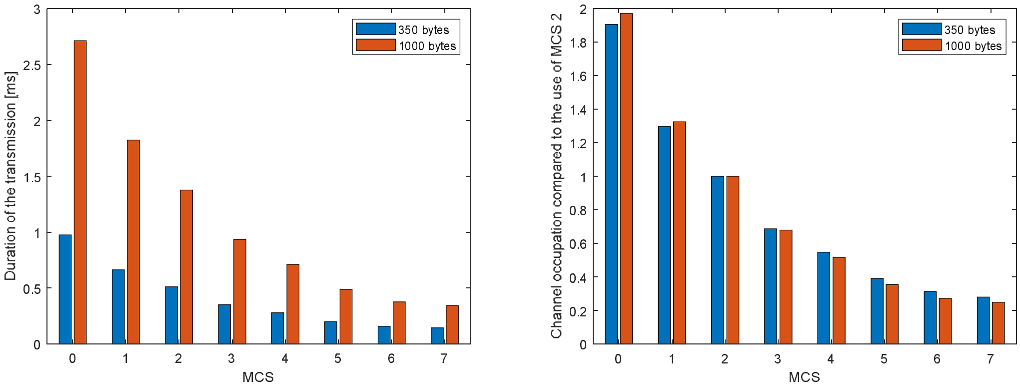
Variations of the power appear complex when looking at control at the facilities layer and also questionably effective: power variations, indeed, affect communication range but do not alter the CBR measurement close to the transmitting vehicle; this causes in turn variable power level and range in the spatial domain, which affects fairness and causes lower overall system performance due to interference coming from hidden nodes. Additionally, if all stations uniformly reduce the power consistently, the effect is only an average reduction of the ratio between the useful signal and the noise power levels, without an improvement of the ratio between the useful signal and the interference power levels [i.23]. Power control may still remain an option when dealing with unicast communications; in such case, in fact, the transmitter may control the power level in order to guarantee a sufficient reliability to the communication while minimizing the interference generated to the others.

Data-rate control appears easier to control at the facilities layer and possibly more effective to control the trade-off between reliability and channel occupation. This means at the access layer to select a different MCS, which corresponds at the facilities layer to the selection of a different ALI. However, the choice of the MCS (or ALI) has also an impact on the range, since higher MCS implies lower protection to noise and interference. Since the header information is always sent with a robust MCS, a data-rate control does not impose additional hidden nodes, even the range for the payload is reduced. The use of data-rate control therefore requires careful considerations about the use cases that need to be supported.

Still discussing the data-rate control, it is also worth observing that the impact may be limited. This is further elaborated hereafter, by assuming the eight MCSs of the basic version of ITS-G5 and calculating the duration of packet transmissions. Based on the specifications of ITS-G5, the duration t_{pck} of a packet transmission with payload of N_{byte} bytes can be approximated as follows:

$$t_{pck} \approx t_h + \frac{\lceil 8 \times N_{byte} \rceil}{n_{bps}} T_{OFDM} \tag{3}$$

where $t_h = 40$ µs is the duration of the Physical Layer Convergence Protocol (PLCP) preamble and header, n_{bps} is the number of useful bits carried by an Orthogonal Frequency Division Multiplexing (OFDM) symbol, and $T_{OFDM} = 8$ µs is the duration of an OFDM symbol. The value of n_{bps} depends on the specific MCS and ranges between a minimum of 24 and a maximum of 216, with 52 used as default (normally known as MCS 2 and corresponding to 4-QAM, coding rate 1/2). The duration deriving from this equation is shown in Figure 9 for packets of 350 or 1 000 bytes. As observable, compared to the use of MCS 2 (which is the default value in ITS-G5), a data-rate control can at most reduce the channel occupation by a factor close to 4; this however requires moving to the less reliable MCS, which strongly impacts on the range. Small variations of the MCS have limited impact on the channel occupation.



(a) Duration of a transmission (b) Channel occupation compared to MCS 2

Figure 9: Impact on channel occupation of data-rate control in ITS-G5

The last option discussed is the transmit rate control, which means controlling the average number of packets sent and can be implemented in two ways. One way is discarding a portion of the packets before they are transmitted, and the other way is to control the generation rate. Looking at the former option, it can in turn be implemented at the facilities or at the access layer. If it is performed at the access layer, there is no possibility to differentiate among packets based on their content and the withdrawal is unavoidably performed in a random way. Among the various options, the control of the generation rate appears clearly preferable and the interaction between the facilities layer and the running applications and services can further help to optimally identify the information to be sent. When referring to Release 1, a withdrawal at the access layer appears as the only viable solution.

Overall, the transmit rate control is the one that can impact more significantly on the channel occupation without affecting communication range. Its main drawback is a reduction of the information update, which is however balanced by a reduction of the packet error rate if the congestion control algorithm works properly.

NOTE: It is observed that transmit rate control is the most effective approach to control congestion; it is also noted that it would be better implemented with a control made by the application rather than by discarding part of the packets. Data-rate control can also help in some cases, if the communication range can be traded-off. Transmit power control seems helpful only in specific cases, such as for unicast transmissions.

5.3.6 Analysis of multi-hop forwarding

What discussed in the previous clauses assumes single hop broadcast communications. In principle, also multi-hop forwarding is however possible, and therefore it also needs to be considered.

Multi-hop forwarding in Release 1 is based on the GeoNetworking protocol (see clause 4.4.5) and follows a packet-centric forwarding approach. In this model, packets are relayed by intermediate ITS-Ss according to geographical addressing information and forwarding rules such as greedy forwarding or contention-based forwarding. This mechanism is performed in the NTL, and it is transparent to the applications and the facilities layer, although it is controlled by them through the choice of packet type and addressing parameters. Packet-centric forwarding ensures that information is delivered to the addressed area without requiring facilities-layer interaction and is particularly suitable for message services with stringent latency or authentication requirements, such as Decentralized Environmental Notification (DENM), where messages need to be disseminated rapidly and without additional processing.

An alternative forwarding concept is information-centric forwarding. In this case, the application or facilities layer interprets the received information, determines its relevance, and generates new messages that may aggregate, filter, or invalidate previously received content. Information-centric forwarding reduces redundancy and can adapt dissemination to the semantics of the information. For example, Cooperative Perception Messages (CPM) may be aggregated before being re-broadcast, and safety-related message services that are not strictly time-critical, such as Signal Phase and Timing (SPAT) and MAP, can benefit from controlled re-dissemination rather than pure packet relaying.

In Release 1, only packet-centric forwarding is supported by GeoNetworking, and there is no integration of information-centric mechanisms at the networking layer. This ensures simplicity and timeliness for critical message services but limits flexibility for other message services that could benefit from aggregation or content-based dissemination. For this reason, the use of GeoNetworking multi-hop forwarding should be restricted to safety-critical messages where low latency is essential or to long range messages that need authentication and that are sent seldom. message services without such requirements should rely on dissemination mechanisms at the facilities layer that are closer to information-centric forwarding.

From a resource management perspective, Release 1 implements congestion control at the access layer through a gatekeeping mechanism that regulates transmission rates based on channel load. This mechanism manages forwarded packets in the same manner as those originating from upper layers, leading to a lack of distinction in how congestion is handled for forwarded traffic. As a result, forwarded packets utilize radio resources without explicit differentiation, which can lead to unpredictable effects during periods of congestion. Additionally, forwarding algorithms may introduce latency due to contention timers, impose an uneven load on stations that engage in more forwarding, and increase overhead in densely populated traffic scenarios. Buffer management is also limited, which may result in packet losses under high load. These limitations suggest that enhancing forwarding efficiency would be advantageous and should be considered for future releases.

An additional aspect for packet centric forwarding is related to the use of traffic classes: In Release 1, the traffic class is a parameter that is passed from the FL through the NTL to the AL. The parameter is used to express the priority of a FL message and map it AL priorities, such as the Access Category (AC) in ITS-G5. In addition, the traffic class represents a data element in the GN header and is transmitted over the air. However, in Release 1, the traffic class is not further to control the forwarding of data packets.

5.4 Interference from adjacent channels

5.4.1 Introduction

The congestion status of a given channel is not only dependent on the actual usage of the channel itself but also on the usage of the spectrum that is adjacent to it. This spectrum might be occupied by interoperable message services using the same protocol or by systems which are not interoperable or compatible. Interference management operations are basically different for the two cases. In the first case, it can be handled by internal RM control operations and functions that are part of the RM specifications. These operations can be called cross-channel RM functions, which include the cross-channel CBR evaluation and the cross-channel load control.

In the non-interoperable case, the cross-channel RM control is not possible due to the lack of interoperability. These effects can only be considered as general interference from adjacent channels similar to co-channel interference from non-interoperable sources.

All non-interoperable interference effects are included in the RM monitoring/evaluation process based on the CBR measurement at the access layer and thus contribute to the channel load in general. It has to be noted that these non-interoperable interference effects can lead to a significant increase of the channel load and to a reduced transmission probability/capability of the ITS systems due to the clear channel assessment performed by CSMA/CA before transmitting. In the RM and the MAC procedure a differentiation between the two different kinds of channel loading effect would be beneficial and could contribute to the proper operation of the ITS.

5.4.2 Impact of interference from interoperable C-ITS in adjacent channels

The impact of interference caused by stations using the same protocols in adjacent channels is extensively studied in ETSI TR 103 439 [i.1].

In Figure 10 the basics of the interfering effects in an MCO operation are depicted with the focus onto the direct adjacent channel as considered in ETSI TR 103 439 [i.1].

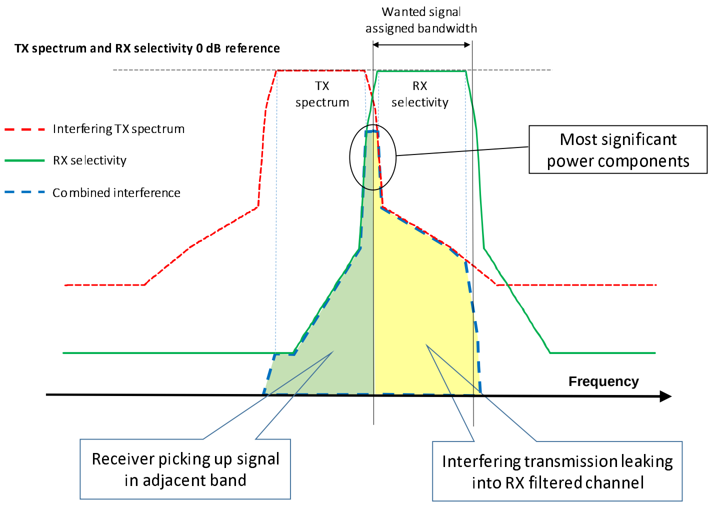


Figure 10: Impact of an interfering transmitter and a victim receiver on the reception of wanted signals

The study in ETSI TR 103 439 [i.1] was performed assuming a highway scenario with multiple lanes per direction and different levels of road traffic. Furthermore, different settings were assumed in terms of which channels were used by the vehicles moving in the scenario. Both cases where similar data traffic was generated on average in the various channels (balanced load) and cases where the load was imbalanced, were considered.

The main conclusions of the study can be summarized as follows:

- When transmissions are performed in channels that are not directly adjacent to each other, the interference that they cause reciprocally only slightly reduces the probability to correctly receive the packets. This also holds even when the channels are congested. This implies that there is no need to take the congestion status of the channels beyond the first adjacent channels into account in the internal RM operations.
- Focusing on transmissions in the first adjacent channel, they do not impact relevantly on the clear channel assessment performed by CSMA/CA before transmitting, but impact on the calculation of the CBR. As a consequence, rarely transmissions are deferred due to interference from adjacent channels, but the interference may increase the CBR and therefore reduce the number of transmissions overall performed in the given channel. When two channels that are directly adjacent to each other are highly loaded, the effect is a reduction of the average number of transmissions due to congestion control, thus a reduction of the collision probability in each of the two channels. This in part counterbalances the increase of errors at the receivers.
- A highly loaded first adjacent channel can cause a reduction of the probability of correct reception of the packets which leads to an estimated loss of range that can reach 25 % to 30 % (where the range is defined as the maximum distance at which a certain minimum reception probability is obtained).
- Distributing the data traffic over two channels, even directly adjacent to each other, is always preferable to having all the data traffic in a single channel. This means that the reciprocal interference caused by transmissions in adjacent channels has an impact lower than the advantage obtained by halving the data load in a single channel.
- Due to the current constraints imposed to the transmission mask, reducing the transmission power in one channel may not significantly reduce the interference it causes to the adjacent channels; even if this also depends on the specific implementation, the observation is that using power control to reduce the interference between adjacent channels may not be effective.
- Reducing the congestion control limit in one channel may reduce the maximum interference that the transmissions in that channel causes to those in its first adjacent channels; reducing the limit in one channel may therefore be used to protect its first adjacent channels.

Given these considerations, interference from stations using the same protocols potentially reduces communication performance in an adjacent channel, but in practice performance degradation does not appear to be critical. It may be helpful to reduce the congestion control limit in some ALI Groups to prevent the communication performance degradation in their first adjacent channels, including the available capacity and communication range. This would give priority to channels with less stringent requirements.

In all the cases, distributing the traffic over multiple channels appears beneficial.

Based on the finding presented in the present document the focus of any RM operation should be on the single operational channel. Adjacent channel effects are mainly relevant when all operation channels are in a high load situation close to a congestion. A single channel RM will keep this effect at a minimum in the first place. Longer term envisaged high load conditions due to a high C-ITS penetration might require some adjacent channel RM optimizations.

Nevertheless, the actual specification of single channel RM work should permit the inclusion of adjacent channel RM in the long-term development.

5.4.3 Adjacent channel monitoring

Different approaches for the monitoring operations of adjacent channel interference can be taken for single channel and multichannel ITS-S. A single channel device cannot differentiate between interoperable or non-interoperable deployments in the adjacent channels without switching to these channels, thus a single channel ITS-S can only passively monitor the interference increase as part of the channel load measurement, independently from the nature.

Multichannel devices can perform this differentiation and can take the required control decisions.

5.4.4 Cross-channel resource management control

In a single channel device, the adjacent channel interference will be treated as normal unspecified channel load element together with the co-channel load elements. The resulting levels of the load estimation in the access layer will be considered in the management algorithms. The co-channel load originating from an interoperable ITS system could be treated differently from the non-interoperable and adjacent channel interference.

In a multichannel device a more detailed view of the interference characteristics in the adjacent channel can be evaluated. This information can be used for an optimization of the RM control algorithm. In order to differentiate between load originating from interoperable systems and load originating from non-interoperable systems, the channel load information from the co-channel and adjacent channel would need to be reported in a structured manner.

5.5 Modifications towards Release 2

5.5.1 Introduction

This clause focuses on the modifications that are proposed to comply with the RM approach in Release 2. Modifications in channels that are already used today should not affect the performance of devices that are already on the road.

To make the proper decisions, the RM should be aware of the radio resources that are available and the radio resources that are necessary to deliver each message. The following clauses therefore discuss the definition of radio resources, the approaches proposed for the determination of the available radio resources, and define the resources consumed by each message.

5.5.2 Radio resources at the facilities layer

A first issue that needs to be solved is how to abstract the radio resources from the access layer to the facilities layer.

The main difficulty is that the resources available and the resources used do not only depend on the average number of bits generated but also:

i) on the number of packets, since each packet has its own headers adding overhead; and

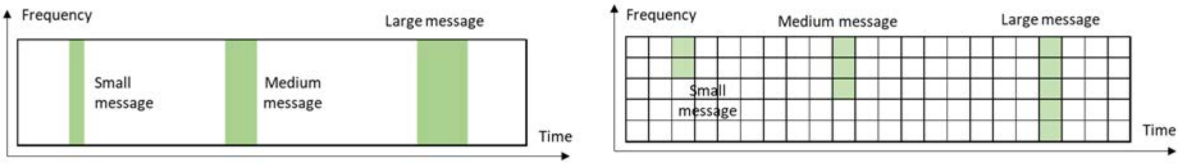
ii) on the specific settings at the access layer, including for example the MCS.

The facilities layer should have, as much as possible, a precise and complete understanding of the options available. It should have for example all the information to decide, under congested situations, if for a given message it is better to use one or the other channel, one or the other MCS, or even discard it.

The knowledge of the available channels and MCSs is already abstracted using the concepts of ALI and ALI group. What still needs work is the definition of the resources, the calculation of the available resources, and the calculation of the resource used to transmit a message in each ALI, possibly with some knowledge about the expected performance corresponding to the use of that specific ALI. The proposed definition of the technology-agnostic resources is as follows:

- Portion of time and bandwidth. This definition is unitless and is valid for any bandwidth or time period. As an example, the resources corresponding to 0,005 are equivalent to the transmission of either:
  a) messages that occupy the whole bandwidth during 0,5 % of the time; or
  b) messages that occupy the half of the bandwidth during 1 % of the time; or
  c) messages that occupy one fifth of the bandwidth during 2,5 % of the time.

This definition is valid for radio access technologies both with and without resource grids. As an example, ITS-G5 (IEEE 802.11 [i.9]) (Figure 11a) makes use of the whole bandwidth in all transmissions, providing a high granularity in time. On the other hand, LTE-V2X and 5G NR-V2X (Figure 11b) allow transmitting using part of the bandwidth but the time duration is fixed.



(a) ITS-G5 (b) LTE-V2X or 5G NR-V2X

Figure 11: Resources in time and frequency

5.5.3 Congestion control in Release 2

In Release 1, the congestion control mechanism is fundamentally performed at the access layer, in which case it is technology-dependent and cannot affect the message generation. In Release 2, the RM functionality needs to be aware of the available resources and to manage them. The following three approaches appear possible:

1) congestion control is performed at the access layer, independently by each ALI group, and the available resources are abstracted to the facilities layer; the access layer provides in this case the available resources, through the networking & transport layer, to the RM; or

2) the access layer provides the information about the channel load to the facilities layer, with the information abstracted so that the facilities layer considers all the ALI groups equivalent; congestion control is then performed at the facilities layer in the same way for all ALI groups; the access layer provides in this case the CBR, through the networking & transport layer, to the RM; or

3) the access layer provides the information about the channel load to the facilities layer, which is configured considering the specific ALI groups; congestion control is then performed at the facilities layer, with ALI group-specific congestion control functions; also in this case, the access layer provides the CBR, through the networking & transport layer, to the RM.

The first solution is closer to what implemented in Release 1, since the congestion control operations are placed at the access layer, but limits the control at the RM; in that case, in fact, the resources that are available per each ALI group are fixed by the access layer. Differently, the other two solutions allow the RM to have more control on the congestion control, for example considering which specific message services are active and with which priority, as explored in clause 7.

The second solution allows to solve the limitations of the first approach maintaining independence from the access technology or technologies implemented; however, it requires that the information provided to the facilities layer and the congestion control algorithm that is implemented at the facility layer are defined technology agnostic, which appears difficult to realize.

For the reasons above, the third solution appears as the preferable solution. It guarantees to the RM the possibility to impact on the congestion control operations, without the need to realize a technology agnostic congestion control function. The main implication of this option is that it requires that different congestion control functions are implemented for the different active ALI groups, or that the implemented function is designed considering the specific ALI groups that are active.

In all the cases, the access layer, in addition to providing the available resources or CBR to the facilities layer, needs to inform it of relevant events, such as queue overflow, drop of packets, and time out of packets; their identification and notification by the access layer need therefore to be specified in Release 2.

5.5.4 Information required by the resource management for the ALI selection

The proposed definition of resources can be also used for the resources needed to transmit a single message. This requires however to map the message size with the resource use. Given that the resources used for a packet transmission depend on the message size and on parameters known at the access layer, one proposed solution is to have at the facilities layer one table per each ALI indicating the resources required to transmit a message of a given size. The table should have at least:

i) one column indicating the message size; and

ii) one column indicating the resources required for the transmission of a message of that size.

Using this table, the RM can calculate the resources it is using and apply procedures that require further work. As a simple example, if the facilities layer has a budget of 0,005 per second for an ALI group, and messages are generated every 100 ms on average, consuming in the selected ALI of that ALI group 0,0001, the RM knows that this flow consumes overall 10 × 0,0001 = 0,001, which is 1/5 of the available resources of the ALI group.

An additional aspect to be considered is that the RM also needs indications on the performance expected when choosing among ALIs that consume different resources. For example, an ALI corresponding to a lower MCS will use more resources than another ALI corresponding to a higher MCS, but the advantage is that the transmission is more robust to noise and interference, which means that it is expected to provide more range. For this scope, one possibility is to store per each ALI a reference one-hop range, which may be for example calculated as the maximum distance at which the error rate is lower than 10 %, assuming a Gaussian channel, absence of interference, and predefined settings for the transmission power and receiver characteristics. As an example, it is assumed that there is one ALI group with two ALIs, ALI A and ALI B; the range of ALI A is 1 km and it requires 0,001 resources (defined as above discussed) to transmit a message of 800 bytes; the range of ALI B is 500 m and it requires 0,0005 resources to transmit the same message; given this information, the RM can decide if it is better to have a longer range but using more resources or the opposite.

5.5.5 Overhead from protocol headers and security

One aspect that needs further clarification is how to account for the overhead added by headers of the protocol stack and security when calculating the total amount of data that will be transmitted over the air.

Headers from NTL and AL protocols add to the overhead:

- At the NTL, BTP and GeoNetworking headers have a fixed size. The GeoNetworking header size, however, depends on the GN transport type (e.g. single-hop broadcast SHB or geographically-scope broadcast).
- The overhead at the AL is technology-specific:
  - For ITS-G5, it includes the LLC header - along with the SNAP sub-header - as well as MAC and PHY header.
  - For LTE-V2X and 5G NR V2X, the overhead is given by the header sizes of the PDCP, RLC, MAC and PHY protocols.

A key point is that the overhead from protocol headers is known in advance of sending a message.

Differently, for the security overhead the size of signatures and certificates is variable and not a-priori known. Consequently, instead of incorporating exact values, it is necessary to use either the maximum estimated overhead or an average estimated value in the RM calculations.

In the context of overhead, it is also worth noting that the maximum size of the payload that can be transmitted in a single FL message is limited and access-technology specific. In Release 1, the size of a GeoNetworking packet sent over ITS-G5 is conventionally limited to 1,500 bytes (see Annex F). Beyond such protocol-specific constraints, the maximum FL message size may also be reduced due to radio-performance considerations: in general, smaller PHY frame sizes are preferred to mitigate synchronization and equalization challenges, particularly under high-mobility conditions. For Release 2, however, a larger maximum message size may be acceptable, taking into account the improved radio performance of the evolution of ITS-G5 based on IEEE 802.11 [i.9]. It should also be noted that for LTE-V2X and 5G NR-V2X other limitations for the maximum data unit apply and depend on the chosen access layer configuration.

5.5.6 Introducing a mechanism for the update of parameters

One feature that is not available in Release 1 and might be worth introducing in Release 2 is the possibility to update the specific value for a limited number of parameters, such as the congestion control limit in each channel. Such updates would require the control from a central entity and a distribution to all ITS-S in a relatively short time, which in turn means that it would require the use of I2V links.

EXAMPLE: One option to be explored is to exploit the distribution of the certificates to also include possible parameter updates.

5.5.7 Networking & transport layer in Release 2

Clause 5.3.6 has shown that, in Release 1, multi-hop forwarding is managed entirely by the GeoNetworking protocol in a packet-centric manner. Forwarding is subject only to the access-layer DCC, which limits transmissions through the gatekeeping mechanism based on channel load. As a consequence, forwarded packets are treated in the same way as packets generated by upper layers, with no explicit coordination or resource differentiation. This can lead to inefficiencies or uneven use of radio resources under congestion.

In Release 2, the FL is expected to participate in the overall RM process, enabling a more comprehensive allocation of resources across message services. With this architectural evolution, different options can be considered regarding how multi-hop forwarding should interact with the emerging RM framework to ensure consistent and efficient use of network resources. Three approaches are identified:

1) Implicit forwarding without RM interaction:
    - GeoNetworking continues to perform forwarding autonomously. The consumed resources are considered negligible and therefore remain outside the RM budget. Optionally, a maximum forwarding rate (in bits/s or packets/s) may be defined locally to prevent excessive forwarding. When this limit is reached, GeoNetworking decides which packets to forward, buffer, or discard. This approach preserves the simplicity and real-time behaviour of Release 1. However, it provides no visibility to RM, which means that the effects of forwarding cannot be considered in admission control or congestion handling (see clause 7.2).
2) Periodic reporting of forwarding resource usage:
    - GeoNetworking estimates the amount of resources used for forwarding and periodically reports this information to RM, for example together with congestion-related metrics such as CBR. RM can then adjust the total available resources for other message services by subtracting the forwarding usage. This allows RM to incorporate forwarding into its scheduling and resource budgeting processes (see clauses 7.3 and 7.4). The approach improves coordination between layers but introduces additional measurement, signalling, and computational overhead within GeoNetworking. In addition, the introduction of priority flags for forwarded packets could enable the network layer to selectively discard lower-priority messages under congestion, ensuring that critical traffic is transmitted first.

3) Forwarding message service abstraction at the FL:

- A dedicated Forwarding message Service (FS) may be defined at the FL, acting as a consumer of resources in the same way as other message services. GeoNetworking would invoke this message service when forwarding is required, and RM would allocate resources through its normal admission control and scheduling mechanisms (see clause 7.5). This ensures homogeneous treatment of forwarding and other message services within the RM framework, offering maximum transparency and control. However, it increases architectural complexity and may introduce additional latency if frequent resource requests are needed for each forwarding action. This works for messages which are signed at the FL but when forwarding is realized according to the Release 1 concept the originating security is lost and the question is how to realize a working mechanism. Further research is needed.

Each approach represents a trade-off between simplicity, control, and implementation complexity (Table 2): Approach 1 maintains architectural simplicity but offers no RM integration. Approach 2 provides moderate integration through lightweight coordination. Approach 3 achieves full integration into the RM framework but requires significant architectural changes and careful design to avoid degrading the responsiveness of safety-critical forwarding.

Table 2: Comparison of approaches for integrating GeoNetworking forwarding into RM

Aspect	1) Implicit forwarding	2) Periodic reporting	3) FS abstraction
Integration with RM	None - forwarding excluded from RM budget	Partial - RM informed of forwarding resource use	Full - forwarding handled as a message service managed by RM
Implementation complexity	Low	Medium	High
Impact on latency	None (same as Release 1)	Minimal increase due to reporting overhead	Possible increase due to RM coordination
Fairness / resource accounting	Not supported	Basic resource accounting	Full resource accounting and scheduling control
Compatibility with Release 1	Full	High	Limited (requires new interfaces)
Suitable for	Safety-critical, low-latency message services	Mixed or adaptive message services	Non-safety-critical or managed message services
Security headers	Send's security headers preserved	Send's security headers preserved	Loss of send's security headers

Implicit forwarding could be sufficient as long as system specifications ensure that forwarding is realized only at the lowest traffic class and that it is only used for functional reasons. Otherwise, the use of GeoNetworking multi-hop forwarding by message services should be limited to safety-critical messages where very low latency and direct dissemination is essential (e.g. DENM). This means that existing message service specifications should be extended to support forwarding as part of its service. To control the forwarding of data packets at the NTL, the concept of traffic classes should be extended.

NOTE: Forwarding should not be used to avoid deployment of additional ITS-Ss.

In addition to the proposed changes in forwarding behaviour, another point to be addressed in the NTL for Release 2 is the handling of the CBR_G. Clause 5.3.2 described how, in Release 1, CBR_G was derived from local, 1-hop, and 2-hop measurements to extend congestion awareness. For Release 2, it is proposed to maintain the inclusion of both 1-hop and 2-hop values to preserve the awareness range, while investigating potential modifications to the aggregation logic. Instead of relying solely on the maximum value, alternative formulations - such as weighted or averaged combinations of received CBRs - could provide a better balance between fairness and efficiency. Further research is required to assess the performance trade-offs and to validate whether these refinements yield measurable improvements under realistic traffic and network conditions.

Finally, given the limited adoption of global CBR sharing in the system profiles defined by C2C-CC [i.7] and C-Roads [i.8], ETSI TC ITS Release 2 should take an active role in promoting the motivation, concept and specification of global CBR sharing, thereby supporting its practical implementation in research prototypes and commercial deployments.

6 Application requirements

6.1 Introduction

To ensure that active applications in an ITS-S are able to make appropriate decisions about when and how to exchange information with other ITS-Ss, they need to be aware of the available communication resources at any given time. In general, more than one application can be active in an ITS-S, and each application does not know the static and dynamic communication requirements from the other applications. The number of active applications in Release 1 is limited but for Release 2 they are significantly extended and therefore some resource management should be considered.

The message behaviour is strongly dependent on the way the dissemination of messages is triggered and the amount of information it needs to disseminate.

Furthermore, dissemination of a specific message type could be triggered by many applications, while other messages may be triggered by a single application or related to a specific use case. The DENM is typically a message type for which the message dissemination can be triggered by multiple applications, while the CAM is a typical message type which is related to a single use case, including message generating rules. The CAM is not triggered by applications but is a stand-alone functionality which has no interface to an application. Any resource management functionality most probably will only have to gather relevant management information for CAM dissemination directly from the CAS but as the DENS only knows that it has to disseminate a message when triggered, any resource management should in the first place get information from the triggering applications and possibly secondary from the DENS. In the following, for relevant dissemination information, reference is only made to applications while for several cases this could be also an message service.

Since in Release 2 implementations the number of active applications is expected to significantly increase, it could be not sufficient to just have the static knowledge about the available resources. Having a generalized knowledge of the needs of all applications could allow a resource management functionality to distribute the available resources between all applications. This could be detailed with different granularity of the resource distribution, which could range from a binary switch-on/off of an application to a very fine allocation of resources to the applications active at any given time.

Different methods exist in the initial Release 2 ETSI MCO concept. For the management of the resource allocation to the active applications in the ITS-S several aspects have to be considered:

- the individual application or message service communication requirements and thus resource needs;
- the application priority;
- available resource management mechanisms and granularity of the resource allocation;
- external resource limitation based on legal and regulatory restrictions.

The first three aspects are ITS-S internal (intra ITS) whereas the last one is external to the ITS-S (inter ITS).

The inter ITS aspect is an ITS intercommunity aspect which might require legal agreements or technical specifications agreed between stakeholders (profiles) to ensure which applications are active when and where in the available spectrum. It will need a secure control mechanism to allow for an external input of the required control information.

C-ITS is defined by the European Union (EU) in the Directive 2010/40/EU [i.31] and its amendments, this EU Directive and related specifications should aim for a robust operation of all C-ITS applications in the assigned C-ITS spectrum.

In the following clauses, the intra ITS aspects related to the way the dissemination of messages is triggered and the amount of information it needs to disseminate them are considered for the known ITS applications and message services.

6.2 Applications and message services

6.2.1 Introduction

There are applications which trigger event message generation and dissemination at the FL by message services (a specific message service) such as the Decentralized Environmental Notification Service (DENS). There are also Message Services (MSs) like Cooperative Awareness Service (CAS) which include message generation rules themselves, by which they trigger the generation and dissemination of messages. However, in future it cannot be excluded that such message services could be triggered as well. In general, message dissemination can be initiated by any application or message service with included message generation rules.

As message services disseminate messages in the same channel as other message service, the dissemination of one message service can be influenced by the message dissemination of one other message service. This dependency does not occur when the channel occupation is not near to the set congestion limits, however, already ahead of the possibility of entering such state, it could be of interest to applications and message services to be aware of this and make different choices when this would apply.

In principle, the understanding of the possible application message triggering and dissemination intensions are required for the realization of resource management. Considering that applications communicate with the ITS-Services and that therefore the message service knows the real disseminations requirements, currently it is considered sufficient that the dynamic behaviour expectations of the message service is communicated to the RM. The RM may also communicate with the applications for more general information, but this is not considered for the time being.

In general, ITS-S-MSs dissemination behaviour can be categorized in three types as follows:

- Broadcasted Event type, such as Decentralized Environmental Notification Message (DENM) triggered by Applications (such as the Triggering Conditions as specified by the C2C-CC [i.7]).
- Broadcasted Awareness types such as:
    - Fixed Repetitive type, with fixed message size, such as MAPEM, IVI and SAM.
    - Adaptable Repetitive type, with predictable but no predefined message size, such as CAM, CPM, SPATEM, MIM/MVM, TLC (SREM, SSEM) and GPC (RTCMEM).
- Broadcasted Streaming type, with fixed rate, fixed size and continuous, such as video streaming.

In the following clauses the message services identified are further detailed with regards to their communication behaviour.

NOTE: The mentioned ITS-S-MS are specified by ETSI and ISO but their references are not provided here as their reference number can differ for difference releases.

6.2.2 Decentralized Environmental Notification Message

The DENM is an event message (as identified in clause 6.2.1). Especially the dissemination of DENMs is triggered by one or more applications which can support the realization of different use cases and environmental scenarios. It can be expected that the number of use cases and scenarios will increase in the future.

Depending on the safety impact of the specific use case, DENM dissemination via direct communication requires a specific priority over other message disseminations. In general, direct communications is direct safety impact oriented and Internet communications indirect safety impact oriented (more details in clause Ecosystems ETSI TR 103 903 [i.4]). While there are ITS use cases best serviced by either one of these communication solutions, there are also ITS use cases which can be serviced by both (see the Hybrid Solution by C-ROADs [i.8]).

One example is the "End of Queue" use case. For this use case the information disseminated via direct communications can be used for a direct stop initiated by a driver of a vehicle or by the automated vehicle itself, while disseminated information via Internet communication will generally be used for rerouting of a trajectory and not predictably for a direct stop, thus they are the same use case but seen as different scenarios. Information disseminated via direct communication (as there are more stringent requirements) can also be used for those use cases which require the same information but can also be serviced by Internet communications. The communication requirements for the indirect scenario are out of scope of the present document.

In Release 1, it was identified that high priority should be provided to these types of messages. It was recognized that events, as they have immediate impact, should be handled first compared to any other kind of other information dissemination. While for Release 1 only two levels were identified, it could happen that for later releases (at present it has not been defined for Release 2) the number of priorities should be extended.

NOTE 1: Extension of the priority levels is not only something of relevance for DEN but also for other message services and therefore a generic extension should be considered.

NOTE 2: Release 1 operational equipment is based on IEEE 802.11 [i.9] which includes four QoS traffic classes (TCs). These TCs are directly coupled to the four priorities used at the FL in C-ITS.

At present two event types can be recognized:

- An event which was not planned, mostly identified by an automated functionality in the vehicle, such as a Slow Driving Vehicle (SDV). This is a type of event which may just popup.
- An event which was planned, typically managed by authorities and switched on and off by humans, such as a Roads Works Warning (RWW).

While with the first type the dissemination of DENMs could take only a very short time, with the second type the disseminations of DENMs could take place for days or even month. This time related aspect is the only difference. Since at present both of the event types can be detected, activated and deactivated, the DENMs will be disseminated with a repetition rate fitting the environment and the use case as required.

From an ITS-S communication perspective, DENM dissemination is not application but use case dependent. In general, an application does not statically know in advance what its communication needs are. Only dynamically, when a use case determines that it needs to disseminate DENMs, the application can notify its needs in terms of resources. This is valid for both the managed and not managed type of events.

Possible parameter consideration for DENM:

- Application statistically (at the time of application activation (application registration)):
    - Application indicator (internal for ITS-S).
    - Number of use cases supported (internal for ITS-S).
    - Expected priority level(s) to be supported.
    - Expected access technology and spectrum requirements (possibly including primary and secondary options).
    - Max message generation rate when activated.
    - Max message size when activated.
- Application dynamically (based on activation of DENM dissemination cycle (application registration)):
    - Application indicator.
    - Use case indicator.
    - Dissemination initiation (Request):
        - Actual priority of the cycle of DENMs to be disseminated.
        - Actual technology and spectrum requirements (possibly including primary and secondary options).
        - Real message generation rate.
        - Real message size.
        - Expected start time of dissemination.
        - Expected termination time.

  - Dissemination termination:
    - ▪ Termination indicator.

NOTE 3: A dissemination cycle is considered to be the period in which a sequence of DENM with a specific rate are actively disseminated.

NOTE 4: At present, a constant rate and constant message size is considered for DENM. Further it is considered that applications realize use cases with a similar message dissemination behaviour.

NOTE 5: To allow any management of the DENM message as provided by several applications and their use cases, it should be clear to the resource management which application/use case initiate DENM dissemination and therefore it is required to provide related DENMs with indicators about which application/use case initiated the dissemination. As a result, each DENM from a cycle needs to include all application dynamic information.

6.2.3 Cooperative Awareness (CA) Message

The CAM is a broadcast awareness message (as identified in clause 6.2.1) disseminated by an ITS-S which represents a road user e.g. vehicle, truck, motorbike, bicycle or pedestrian. The CAM provides information about the dynamic state of the represented road user. This information includes parameters such as location, time and dynamic parameters as speed and direction.

Since a CAM only provides information about its own identified road user, it is considered as a single use case only.

As specified in the CA ITS-S-MS specifications, the dissemination has two specific characteristics:

- The message dissemination rate depends on the dynamic behaviour of the station. In principle, it depends on the speed, acceleration and movement. The dynamic dissemination behaviour is expected to depend on the type of represented road user and can differ for a vehicle compared to a bike.
- The information to be shared as part of the CAM includes static as well as very dynamic parameters. As it is not that relevant to exchange the static parameters too often, related information is shared not as often as for the dynamic parameters, with the result that the disseminated message has a regular but not constant message size.

CAM transmission can therefore be predictably estimated but depend on the environment (for vehicles, it differs for urban, sub-urban and highway). CAMs predictability depends on the intelligence of the system which disseminates these messages. This can be statically performed or done in various dynamic ways, including the use of Artificial Intelligence (AI).

Possible parameter consideration for CAM:

- Application statistically (at the time of application activation (application registration)):
  - Application indicator (internal for ITS-S).
  - Number of use cases supported (fixed = 1 for the time being) (internal for ITS-S).
  - Expected Priority level(s) to be supported.
  - Expected Technology and spectrum requirements (possibly including primary and secondary options).
  - Maximum message generation rate.
  - Minimum message generation rate.
  - Maximum message size.
  - Minimum message size.
  - Distribution type.
- Application dynamically (based on activation of CAM dissemination (application registration)):
  - Application indicator.

- Use case indicator (fixed = 1 for the time being).
- Dissemination initiation (repeatedly based on environmental changes) can be repeated as long as needed:
    - Actual Priority of the cycle of CAMs to be disseminated.
    - Actual Technology and spectrum requirements (possibly including primary and secondary options).
    - Expected average message generation rate.
    - Expected maximum message generation rate.
    - Expected minimum message generation rate.
    - Expected average message size.
    - Expected maximum message size.
    - Expected minimum message size.
    - Required operation limit message rate.
    - Expected start time of dissemination.
    - Expected termination time.
    - Distribution type.
- Dissemination termination (for instance when the vehicle is parked).

6.2.4 Collective Perception (CP) Message

The CPM is a broadcasted awareness message (as identified in clause 6.2.1) that is continuously generated with variable interval and message size. The variable interval comes from the fact that the CPM is only generated when certain rules are satisfied and not based on a predefined interval. The CPM includes information recognized by the equipment from which the ITS-S is part off. The disseminate CPM can include (a subset of) the objects perceived by the station, information about the sensing capabilities, and information about the perception regions.

The present Collected Perception Service (CPS) specification specifies a set of perceived object inclusion rules that significantly and dynamically influence the CPM size and generation rate (or interval). These rules are mainly based on the dynamics (e.g. position and speed) and type (e.g. VRUs vs vehicles) of the perceived objects. These object inclusion rules were extensively studied in related ETSI studies and in the scientific literature (see [i.25] and [i.28]). The CPM generation rules also include the possibility to dynamically include in each CPM a variable number of objects taking into account their value or utility, which is referred to as Value of Information (VoI) which refers to as redundancy in the scientific literature [i.26] and [i.27]. In addition, the object inclusion rules defined in the CPS standard allow the adaptation of the CPM size (or number of perceived objects) and interval based on inputs from RM. This ensures that the resources are used efficiently, and the amount of information sent by the collective perception service fits into the radio channel.

As specified, the sender can design its own rules about the inclusion of perceived objects (with *ObjectInclusionConfig* flag set to "0"), which affect the CPM size and rate. The CPM is considered to support multiple use cases as the perceived objects represent different traffic participant types and other types such as empty road slots. As different traffic participant types could represent different message sizes and generation rules, one CPM can include objects representing of traffic participant types of one kind while other CPMs include objects representing of traffic participant types of one or more other kind. Also, for other reasons linking specific use cases to specific CPMs is advisable. This means not to disseminate object information of all objects recognizable by the sensor but select those object information relevant for the use cases to be supported. For system flexibility and robustness, it is advised not to include all the perceived objects in a single CPM. One of the main reasons is to avoid reaching the maximum message size and requiring the allocation of more than 10 MHz bandwidth. In general, from a system perspective it is better to keep awareness messages small so there is flexibility of making system choices.

For the rest for CPM the same applies as for CAM.

6.2.5 MIM and MVM

The Marshalling Infrastructure Message (MIM) and the Marshalling Vehicle Message (MVM) are used by the Automated Vehicle Marshalling (AVM) service or low-speed remote controlled automated driving (e.g. in parking areas or factories). The MIMs are disseminated by the infrastructure and the MVM are disseminated by vehicles.

Each MIM sent by the infrastructure can target up to 32 vehicles and therefore its size can significantly change over time depending on the number of vehicles being remotely controlled. The MVM sent by vehicles have optional elements that also generate messages with variable size, but its variation is significantly lower than the MIM.

A sequence of MIMs and MVMs are exchanged during the initialization of the AVM service. During the driving mode, the infrastructure and the vehicle have to periodically exchange MIMs and MVMs for the correct operation of the message service. To this aim, the AVM service introduces a message generation based on a mix of periodic and event-driven messages. By default, AVM messages are generated continuously at a recommended rate of 10 Hz. Additionally, the generation of MIMs and MVMs may be triggered by events, such as emergency stops. These events may cause the generation of one or more new messages and thus disrupt the periodic pattern.

With regards to message dissemination behaviour, it can be expected that it has a more static behaviour as CAM but at high rates. It can be expected that the parameter set is quite similar to CAM/CPM.

6.2.6 Signal Phase and Timing Message (SPATEM)

SPATEMs are semi-static messages which means that their size can slightly change. The timing of the SPATEM depends on the changes in the traffic-light behaviour. Today's dynamically SPATEM assigning systems could update the sequence about once every 0,1 second. So, updates of 10 Hz are not an exception. The packages however are not large and both size as update rates although dynamic are still quite predictable. With regards to channel use, only Roadside Units (RSUs) will transmit SPATEMs and therefore it can be expected that in a range of 200 m to 400 m only a very few RSU will transmit. After analysing the SPATEM, it can be recognized that the SPATEM can use the same parameter structure as the CAM and only will have different values.

6.2.7 MAP Message (MAPEM)

The MAPEM messages are static messages which provide an overview over the road topology with all lane descriptions and stop lines etc. The size always stays the same and it is disseminated with a fixed lower frequency such as 1 Hz to 2 Hz by RSUs. Like for SPATEM, the same parameter structure as for CAM plus additional parameters taking their Geobroadcast nature into account. can be used.

6.2.8 In Vehicle Information Message (IVIM)

The IVIM is a message which is intended to represent for instance a sign. A sign is expected to be static, like a speed limit sign. However, road operators do change the prelimits depending on the situation on the road. Signs can therefore be static or semi-static (changing ones in a while, in intervals of minimal 30 seconds).

IVIMs are awareness messages which can only be disseminated by authorities which could be RSUs but also special vehicles. Like SPATEM and DENM they are generated by authority controlled ITS-Ss. The number of ITS-Ss within a certain vicinity will be limited. It can be assumed not to be more then 4. The impact on the channel use can be assumed minor.

The size is known and static while the rate may be of a few Hz and it can slightly change depending on the road it is active. The dissemination is timely predictable to allow a resource management functionality to fulfil its task. The same parameter structure as for CAM plus additional parameters taking their Geobroadcast nature into account. can be used.

6.2.9 Service Announcement Message (SAM)

At present from a message dissemination perspective, the SAM can be seen similar to the IVIM. The SAM is not yet considered to be used for the announcement of dynamic safety use cases, which could result in some additional dissemination requirements (at present this is not foreseen). SAM dissemination can be predicted sufficiently to allow resource management to fulfil its task. The same parameter structure as for CAM plus additional parameters taking their Geobroadcast nature into account can be used.

6.2.10 Vulnerable road user Awareness Message (VAM)

The VAM is an awareness message similar as the CAM its size is smaller and rate more predictable and lower. Considering road scenarios, the number of present VRUs in an area could however be much more then Vehicles in the same area. The dynamic behaviour of VRUs is much slower than that of Vehicles and therefore the channel use behaviour is likely to be more predictable for the RM than that of the dissemination of CAMs. The same parameter structure as for CAM plus additional parameters taking their Geobroadcast nature into account. can be used.

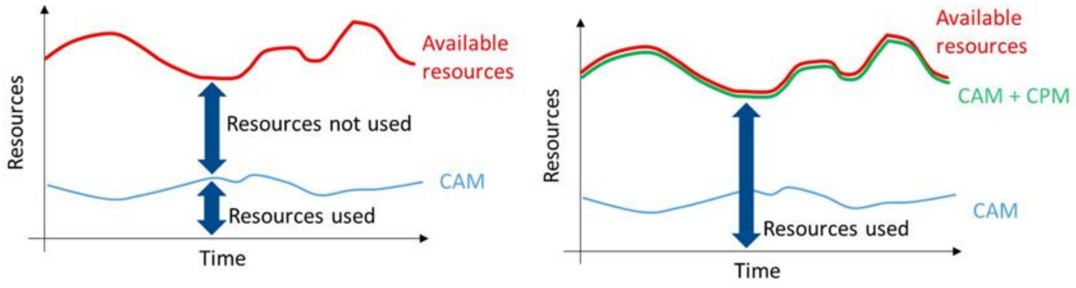
6.3 Types of message services from RM perspective

The envisioned RM solution will provide indications to the message services so that they can dynamically adapt the messages they generate in real time. To this aim, the message services could reduce the number of messages and/or their size to follow the indications provided by the RM, while at the same time send additional messages to be offloaded to alternative channels. In this context, the following types of message services are identified:

- Size adaptation message services that adapt the message size (dynamic inclusion of objects in CPMs or vehicles in MIM, or optional elements in any other Message service) but keep the message interval fixed.
- Interval adaptation message services that adapt the interval of the message generation instead of adapting their size.
- Size and interval adaptation message services that have the flexibility and intelligence to adapt both the message interval and size following the indications of RM.

According to how the message services generate their messages, the following types are also envisioned:

- Predefined rules message services that have their own message generation rules that trigger the generation of new messages. When enough resources are available, they generate the necessary messages following these rules. If the available resources are higher than the resources needed by these message services, they simply follow they predefined message generation rules. Examples are the CA and DEN services (see Figure 12a).
- Adaptive rules message services that adapt the messages they generate to the resources available. The more resources available the more messages they can generate, up to a certain limit that can be high. One example is the CP service, that could adapt the number of perceived objects and regions following the instructions of the RM (see Figure 12b).



(a) CAM

(b) CAM and CPM

Figure 12: Illustration of resources consumed by CAM and CPM

6.4 Heterogeneous resource requirements

6.4.1 Same services but different resource needs

One important aspect to consider in the design of the RM is the fact that two (or more) ITS-S could be running exactly the same message services, but the radio resources each one consumes can differ widely. Some examples are described below:

- **Cooperative Perception Service (CPS).** An ITS-S on a vehicle typically detects less objects than an ITS-S on an RSU, so that the amount of information they need to generate is different. Also, two nearby vehicles can also detect a very different number of objects based on their specific location and sensors. The quality of the sensors is also an important factor, since the quality of the detections has an impact on the amount of information that needs to be transmitted.

- **Automated Vehicle Marshalling (AVM).** Vehicles participating in an AVM system transmit Marshalling Vehicle Messages (MVMs). The infrastructure controlling these vehicles generates Marshalling Infrastructure Messages (MIMs) that are larger in size and have to be more frequently transmitted (see for more information the publication "Automated Vehicle Marshalling" [i.29]). Even though both participate in AVM, their resource needs are intrinsically asymmetric.

- **Cooperative Awareness (CA).** Two implementations may have different resource requirements depending on the optional elements implemented, and the specific driving conditions. As an example, a vehicle could be in a traffic jam in one driving direction and a nearby vehicle could experience free flow conditions in the other direction. The CA service of the vehicle stopped would generate CAMs at 1 Hz, while the other could require the transmission of CAMs at 10 Hz depending mainly on its speed.

The design of the RM should be able to handle this heterogeneity of resource needs to optimize the bandwidth efficiency and system performance.

6.4.2 Different stations with different needs

The resources needed by different ITS-S also depend on the number of Message services they implement or their Release, since they are expected to implement different message services in each release. Some examples are shown below:

- A Release 1 ITS-S generates essentially CAMs and only occasional DENMs.

- A Release 2 ITS-S also implements collective perception, so it generates CPMs in addition to CAMs and sporadic DENMs.

- A Release 3 ITS-S could also implement manoeuvre coordination, generating extended Manoeuvre Coordination Messages (MCMs) in addition to CPMs, CAMs and DENMs.

On any given road different ITS-S implementing different Releases can be intermixed, each with its own resource needs-ranging from a lightweight CAM-only sender to a fully-featured node that generates CAM, CPM, MCM and DENM concurrently. The design of the RM should ideally take into account these aspects.

6.5 Indications to message services

Message services will dynamically adapt the messages they generate (size and/or interval) following the indications of RM. Different options are possible with different levels of abstractions for the RM to inform the ITS-S about the messages they can generate:

- **Bits/s.** The RM could limit the amount of bits/s that each ITS-S can generate in the default channel (or alternative channels). With this approach the message services could adapt e.g. the message interval for a given size.

- **Bits.** The RM could assign a certain number of bits to the message services to indicate them that they are allowed to generate one or more messages so that the total amount of bits does not exceed the assigned one, irrespective of the time. In the next update, the RM could take into account if the message services consumed all the bits assigned or not, and re-assign them accordingly. This approach is similar to the previous one but avoids the complexity of time management in the message services, since they only have to check the number of assigned bits left to generate new messages.
- **T_{on}/T_{off}.** This approach was used in Release 1 as detailed in clause 5.2. Radio access technologies like LTE-V2X and 5G NR-V2X would not support this approach because they have a fixed T_{on}, except in those cases where one facility-layer message has to be segmented in multiple packets at the access layer.

6.6 Conclusions

At present, there are two types of Message Services (MSs) identified. The first type corresponds to those that directly use the sensors information to generate and disseminate messages, such as CAS, and therefore should autonomously register to an RM service when present. The second type corresponds to those where the generation and dissemination are triggered by applications. In this case, in principles, the applications should have knowledge about the dissemination needs; however, present known applications do not have direct control on the disseminated messages but only provide basic data element requirements and trigger or cancel commands to an MS, which implies that it is not needed that these applications register to the RM. Therefore, at present, both types can behave with the MS communicating with the RM.

In case RM functionality is present in an ITS-S, MSs should register to the RM service and inform the RM about changes in their dissemination needs. In return, MSs should receive back from the RM the limitations at any time that the limitations change. This information exchange is realized through a control interface between the RM and all active MSs.

In case RM functionality is present in an ITS-S, an MS provides initiated disseminations to the RM, allowing the RM to control the real disseminations. The RM could in case of issues inform the MS about misbehaviour or unknown changed restrictions.

With regards to the dissemination requirements of MSs, an MS should at least provide these requirements through the control interface, but it may also be relevant to allow this information being part of the FL payload in the data path.

MSs should provide at least the following minimum set of parameters:

- Principle dissemination path requirements (ALIgroup or ALIgroups + possible technology specific) parameters.
- Requested bandwidth with related expected time period.
- Expected packet rate in the same time period.

MSs could provide additional parameters such as:

- Secondary (alternative) dissemination path requirements (ALIgroup or ALIgroups + possible technology specific) parameters.
- Requested bandwidth with related expected time period.
- Expected packet rate in the same time period.

The RM should communicate with the message services using appropriate metrics. The main options considered to define the requested bandwidth are in terms of bits per second (bits/s) or in bits per update period. This latter approach offers an advantage by simplifying time management for the message services, as they only need to check the remaining allocated bits before generating a new message, ensuring that the dynamic adaptation of size and/or interval remains within the assigned resource limits.

The design of the RM solution should recognize that message services have the capability to dynamically adapt their generated messages by modifying either the message size, the generation interval, or a combination of both, according to RM indications. The solution designed will have to provide sufficient flexibility to the message services to adapt the messages they generate to their needs.

Another important aspect is the intrinsic heterogeneity in the resource requirements of ITS stations. On any given road, stations with very different capabilities can coexist, ranging from older ones (Release 1) that primarily generate CAMs and sporadic DENMs, to newer ones that also include CPMs and MCMs. This mix of lightweight and fully-featured nodes increases the complexity of the RM operation and underscores the need for the RM to intelligently manage different demands. In addition, even when running the exact same service, such as Cooperative Perception (CP) or Cooperative Awareness (CA), different stations may consume different resources. Factors such as specific location, driving conditions (e.g. congestion vs. free flow), sensor quality, or the station's role (e.g. in an Automated Vehicle Marshalling or AVM system) lead to substantial asymmetry in the quantity and frequency of data that needs to be transmitted. All these aspects will need to be taken into account in the design of the RM solution.

7 Resource management concepts

7.1 Introduction

Resource management plays a pivotal role in ensuring efficient operation and Quality of Service (QoS) in communication systems. The FL is particularly well-suited for this task, as it can integrate the capabilities of lower layers with the dynamic functional requirements of message services. As highlighted in the Multi-Channel Operation (MCO) concept study in ETSI TR 103 439 [i.1], ITS-S-MS at this layer are unaware of the communication needs of other ITS-S-MS. This necessitates a robust Resource Management (RM) functionality to ensure a consistent and efficient use of available channels.

The RM ITS-S functionality should be seen as an improvement of the original MCO functionalities as specified by the set of MCO specifications. The RM operates by harmonizing dataflows between message handling services to realize improved trustworthiness and QoS while making an efficient use of the channels. It leverages the capabilities of lower layers while supporting technology agnostic operation of message-disseminating message services. This layered approach ensures that resource allocation and communication management remain dynamic, adaptive, and aligned with real-time network conditions. The following clauses outline key concepts and mechanisms for resource management, drawing analogies to wired network practices while addressing the unique requirements of vehicular networks.

7.2 Analogy with wired networks

Resource management in vehicular networks shares conceptual similarities with wired networks, particularly in the context of resource reservation and QoS. In wired networks, clients request resources for specific flows, defining the flow parameters and QoS requirements. The network evaluates these requests and accepts them only if all nodes along the path can support the resource demands. Nodes include edge and inner nodes ensuring seamless communication. Figure 13 illustrates resource reservation for QoS flows in wired networks.

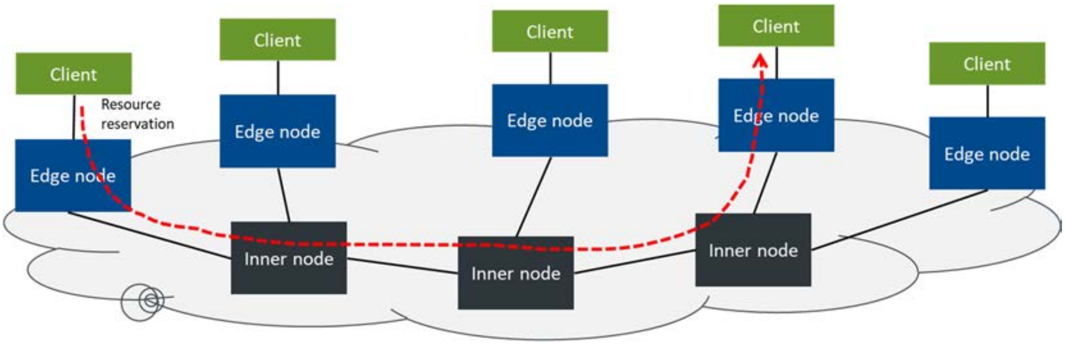


Figure 13: Resource Reservation in Wired Networks

In vehicular networks, this analogy holds with certain adjustments. Here, applications or message services act as clients, requesting resources for message dissemination based on their QoS needs. The RM evaluates these requests and grants or denies them based on channel availability and service priority. Unlike wired networks, vehicular networks lack intermediate nodes for resource validation. Instead, the system uses channel load measurements for resource management. This model supports dynamic and adaptive resource allocation tailored to the real-time demands of vehicular communication systems. Figure 14 shows how the concept of resource reservation can be adapted to vehicular networks.

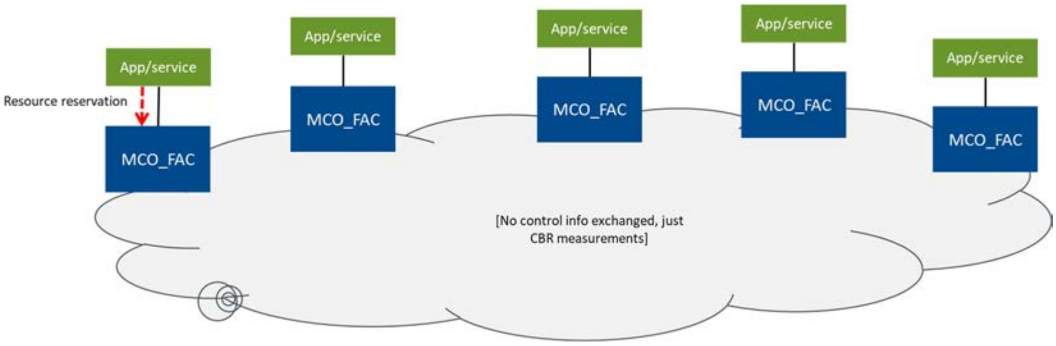


Figure 14: Resource Reservation Analogy in Vehicular Networks

The trustworthiness and QoS of the vehicular network are not guaranteed by RM. RM is only able to manage and supervise the dissemination of the messages. In wired vehicular networks the trustworthiness and QoS are fixed by the system design, which is a closed box approach in which it is known what network can be expected at least in terms of congestion.

In the ITS, this should also be managed. This management is handled by an agreement between the stakeholders on what use cases and message services are allowed to exchange their message in the specific available radio channel or channels.

7.3 Resource management architecture and its mechanisms

7.3.1 Overview

This clause describes mechanisms for resource management that can be part of the RM functionality, in particular mechanisms that can be used in Bandwidth Management Component (BMC) and Message Handling Component (MHC), as defined in the MCO architecture.

For the RM, the BMC can include functionalities such as admission control and bandwidth management. These functionalities require the BMC to collect application requirements, monitor channel conditions, and configure radio interfaces:

- The admission control functionality is critical in regulating resource usage when a message service is activated. It evaluates resource availability and prevents the activation of message services that exceed current bandwidth or violate predefined priorities or regulatory constraints. See clause 7.3.2 for details on different admission control techniques.

- The Bandwidth Management functionality ensures the adaptive allocation of radio resources to meet varying traffic demands. This mechanism is applied exclusively to message services that have been admitted through admission control, ensuring that only authorized message services utilize the available bandwidth. Additionally, the priorities of the messages are a key factor in bandwidth management. Higher-priority messages, such as safety-critical notifications (e.g. DENMs), are allocated bandwidth preferentially to ensure timely delivery. By dynamically adjusting resource allocation in real-time based on priorities and current conditions, this approach optimizes performance while adhering to predefined admission policies. This approach adjusts bandwidth allocation in real-time based on service requirements and current conditions. See clause 7.3.2 for examples of bandwidth management techniques.

The MHC can implement traffic shaping and traffic policing policies to manage the transmission of messages effectively, ensuring compliance with the configuration limits set by the BMC:

- The traffic shaping policies can be used to smooth and regulate the traffic generated by each message service, buffering or delaying excess traffic to ensure long-term compliance with traffic limits. The MHC can be responsible for performing this task to ensure that each message service adheres to its allocated bandwidth and complies with the resource management policies defined by the BMC. For common algorithms see clause 7.3.4.

- Traffic policing ensures strict traffic limits by marking or discarding excess traffic without buffering. This enforcement guarantees that the aggregation of all the messages generated by the message services and sent down to the lower layers operate within their permitted limits, maintaining overall network stability and fairness. See for more details clause 7.3.5.

These entities work collaboratively to optimize resource allocation and maintain QoS in vehicular communication systems. Figure 15 illustrates how these mechanisms could be integrated into the BMC and MHC of RM.

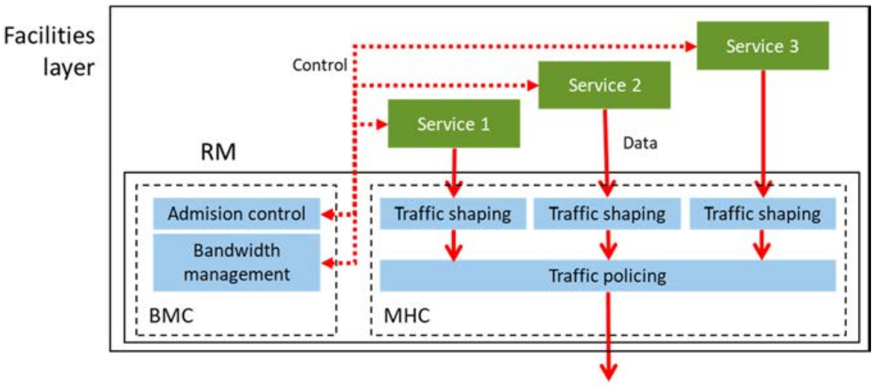


Figure 15: Architecture and mechanisms for Resource Management (RM) at the facilities layer

The RM can be implemented in a synchronous or in an asynchronous way. Synchronously by synchronizing to a system heartbeat which could be the maximum CAM repetition rate (or twice) of any other relevant heartbeat. It can also be realized asynchronously but just waiting for changes in the MSs dissemination requirements, the available radio resources or issues detected in the message dissemination flow (see clause 7.4 for details). Overall, it is expected that an asynchronous implementation allows a more efficient implementation however this is not proven.

In the following clauses these aspects are detailed and highlighted.

7.3.2 Admission control techniques

Peak Resource-Based Admission Control: Limits resource allocation based on the peak resource demands of a message service. It avoids allocating resources that might exceed network capacity during peak usage periods. A practical example is restricting the activation of multiple message service with a high peak message generation rate during a traffic jam.

Average Resources Admission Control: Ensures that the cumulative resource usage remains within bounds by summing up the average resource demands of all active message services. This typically involves adding average resource demands, rather than peak values that could be rarely produced. For instance, this method might deactivate a message service when the sum of average resources is higher than the available resources.

Equivalent Bandwidth Admission Control: Allocates resources based on the equivalent bandwidth required for a message service, considering both average and peak demands. The equivalent bandwidth is calculated by combining the statistical distribution of traffic loads with the desired QoS parameters, such as delay, jitter, and packet loss rate. For example, if a message service exhibits bursty traffic patterns, the equivalent bandwidth will factor in both the average rate and a margin to accommodate bursts, ensuring reliable operation. This approach is well-suited for message services where peak demands need to be balanced against average usage to optimize resource allocation. This approach provides a more realistic estimation of resource requirements compared to simple peak or average calculations.

Statistical Admission Control: Utilizes probabilistic models to estimate resource requirements and allocate them based on expected traffic patterns. Unlike equivalent bandwidth control, statistical admission control focuses on the likelihood of multiple message services requiring peak resources simultaneously. This approach uses historical data and probability distributions to anticipate resource needs, ensuring that resources are not over-allocated based on rare peak scenarios. In practice, it might prioritize safety-critical messages during periods of high traffic density, while reserving capacity for unexpected spikes in demand.

Policy-Based Admission Control: Implements resource constraints based on pre-defined policies, such as user priority levels or regulatory requirements, ensuring that critical message services receive necessary resources. This method can be combined with other admission control mechanisms. For instance, policy-based rules can complement Statistical Admission Control by defining thresholds for resource allocation under specific conditions, such as prioritizing certain messages during congestion. Similarly, it can enhance Equivalent Bandwidth Admission Control by incorporating policies that adjust the equivalent bandwidth calculations based on application-specific or regulatory priorities, ensuring more granular and adaptive resource allocation. For example, a policy might specify that safety-critical messages always have precedence over awareness messages, regardless of statistical or bandwidth estimates.

7.3.3 Dynamic bandwidth management techniques

Proportional Fairness: Balances resource distribution equitably among applications and message services by ensuring that each of them receives a fair share relative to its needs, promoting overall network efficiency. Message priorities play a critical role in this mechanism. Messages are grouped by their priority levels, and resources are allocated proportionally within each group. For multiple priority levels, higher-priority groups are allocated resources first, and any remaining bandwidth is distributed among lower-priority groups using proportional fairness. For instance, DENMs (high-priority messages) are served first to ensure safety-critical operations, while CAMs and CPMs share the remaining bandwidth in proportion to their demands (assuming that they have the same priority).

Max-Min Fairness: Prioritizes applications and message services with the least resources by maximizing their resource allocation without significantly impacting others, ensuring minimum fairness for all users. Message priorities are also important in this context. High-priority messages are allocated resources first, ensuring their timely delivery. Once higher-priority demands are satisfied, the remaining resources are distributed among lower-priority messages in a way that maximizes the minimum allocation, ensuring no message service is entirely starved of resources.

Message Generation Scheduling: This advanced technique involves the BME directly controlling the scheduling of message generation by message services. The BME considers the available bandwidth, current channel conditions, and message priorities to decide when each message service can generate a new message. For instance, higher-priority messages might be scheduled for immediate generation, while lower-priority messages are deferred to avoid congestion. This approach ensures an optimal balance between resource utilization and the timely delivery of high-priority messages.

Machine Learning-Based Management: Applies predictive analytics to forecast traffic patterns and optimize bandwidth allocation proactively. Machine learning algorithms can also account for message priorities by learning from historical traffic patterns and adapting allocation strategies. For example, the system might predict an increase in high-priority messages and pre-emptively allocate bandwidth to accommodate this demand, ensuring timely message delivery across all priority levels.

7.3.4 Traffic shaping policies

Token Bucket Algorithm: Controls the flow of traffic by allowing bursts within a limit, regulated by token generation rates. The algorithm internally uses tokens, which are generated at a constant rate, to authorize the sending of packets. Each packet consumes a token, and traffic exceeding the token rate is delayed until tokens are available again. This mechanism ensures compliance with average traffic rates while permitting flexibility. For instance, it can handle sudden bursts of messages without disrupting other message services.

Leaky Bucket Algorithm: Smooths traffic by enforcing a constant output rate, discarding excess data beyond the bucket's capacity. The algorithm uses a fixed-size bucket where packets are added at any rate but are released at a steady, predetermined rate. If the bucket overflows, excess packets are dropped. This ensures a steady flow of traffic and can be used to regulate bursts of messages to avoid network saturation.

Dual Token Bucket Algorithm: Combines two token buckets to manage multiple traffic priorities. The primary bucket regulates high-priority traffic, while the secondary bucket manages lower-priority traffic. High-priority traffic consumes tokens from the primary bucket, ensuring prompt transmission, while lower-priority traffic waits until both buckets have sufficient tokens.

Virtual Scheduling Algorithm: Simulates scheduling in a virtual timeline, ensuring fair distribution of resources by assigning each packet a virtual departure time. Packets are sent in the order of their virtual departure times, maintaining compliance with predefined traffic limits. This could prioritize transmission of event-driven messages over general status updates, ensuring timely delivery of essential information.

Generic Cell Rate Algorithm (GCRA): Monitors and regulates traffic based on cell arrival times to ensure adherence to the specified rate and burst tolerance. GCRA uses a virtual scheduling mechanism to check if incoming packets comply with the configured traffic profile. Non-compliant packets are either dropped or marked.

Sliding Window Algorithm: Controls the rate of data transmission by monitoring traffic over a moving time window. It calculates the volume of data sent during the window and ensures it does not exceed a predefined threshold. If traffic exceeds the limit, packets are delayed or dropped. This technique can be employed to manage the steady flow of messages from vehicles during a convoy, maintaining a balance between throughput and compliance with traffic limits.

7.3.5 Traffic policing policies

Unlike traffic shaping, which smooths traffic over time by buffering excess data, traffic policing focuses on immediate compliance by dropping or marking traffic that exceeds the defined limits. This ensures that the system adheres strictly to resource policies without introducing delays caused by buffering. Traffic policing mechanisms often include techniques similar to those used in traffic shaping, such as the Token Bucket and Leaky Bucket algorithms. However, in traffic policing, these mechanisms enforce strict limits by discarding non-compliant packets instead of buffering them. Figure 16 illustrates the differences between traffic policing and shaping when they are applied to the same message flow. In the figure, the vertical axes represent the message rate, and the horizontal axes represent the time.

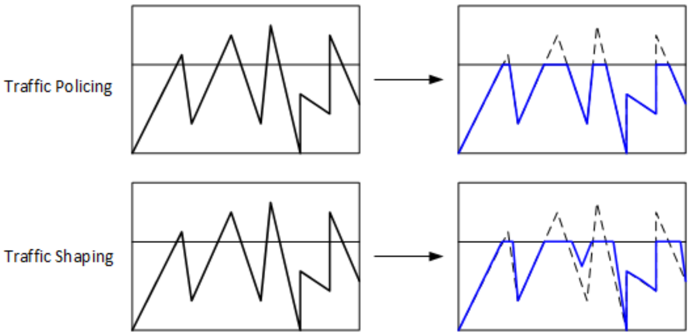


Figure 16: Effect of traffic Policing and Shaping on a message flow

7.4 Resource Management operation

The operation of RM is closely linked to the behaviour of lower layers, since it relies on channel load measurements to assess dissemination possibilities. As these measurements take time and are updated frequently to ensure stable resource management, the timing of RM should be aligned with the optimal channel load measurement period. There should be a direct relation between the channel load measurement period and the RM period. For instance, a new RM cycle could start every n channel load measurement periods (with $n \in \{1,2,3,\ldots\}$). Additionally, filtering mechanisms might be required to smooth fluctuations in channel load measurements, particularly if shorter measurement periods are used. Finally, the potential synchronization of channel load measurements across ITS-Ss should also be evaluated.

RM can also be triggered by message services or applications. In this case, dissemination requirements are still provided by the message services, but the triggering is message service-driven rather than bound to a fixed schedule. This enables message service-triggered RM interactions, for instance when a safety-critical sequence of messages requests immediate transmission. Such an approach reduces the latency for specific messages, though at the cost of increased complexity. It also implies that message services do not need to operate synchronously; instead, they may function independently according to their own pace. Since each application or message service may have its own update rate, defined either statically or dynamically, it is difficult to prescribe a single RM operation model. Instead, RM should be flexible enough to adapt to the timing needs of the message services it supports.

Two main approaches can be envisaged. First, a periodic approach where RM operates according to channel load measurement cycles and checks for updated message service requirements during those cycles (Figure 17). Second, an interrupt-based approach where RM is triggered whenever an message service registers or updates its requirements, making decisions based on the most recent channel load values (preferred in many cases, though ultimately an implementation choice). A hybrid solution combining both approaches may also be envisaged (Figure 18).

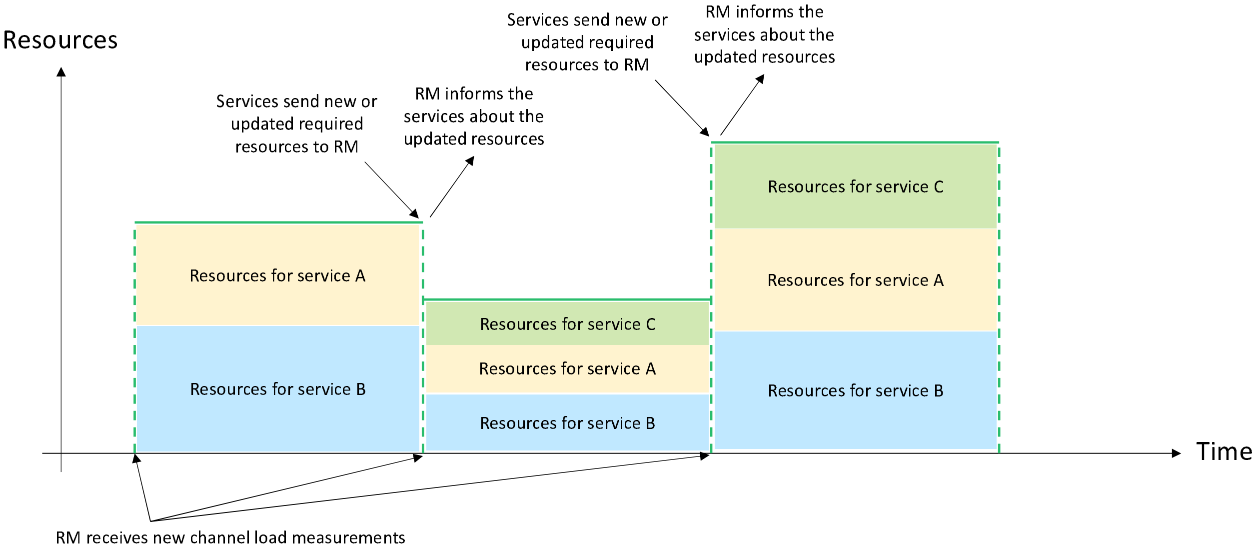


Figure 17: RM workflow with periodic operation driven by channel load measurements

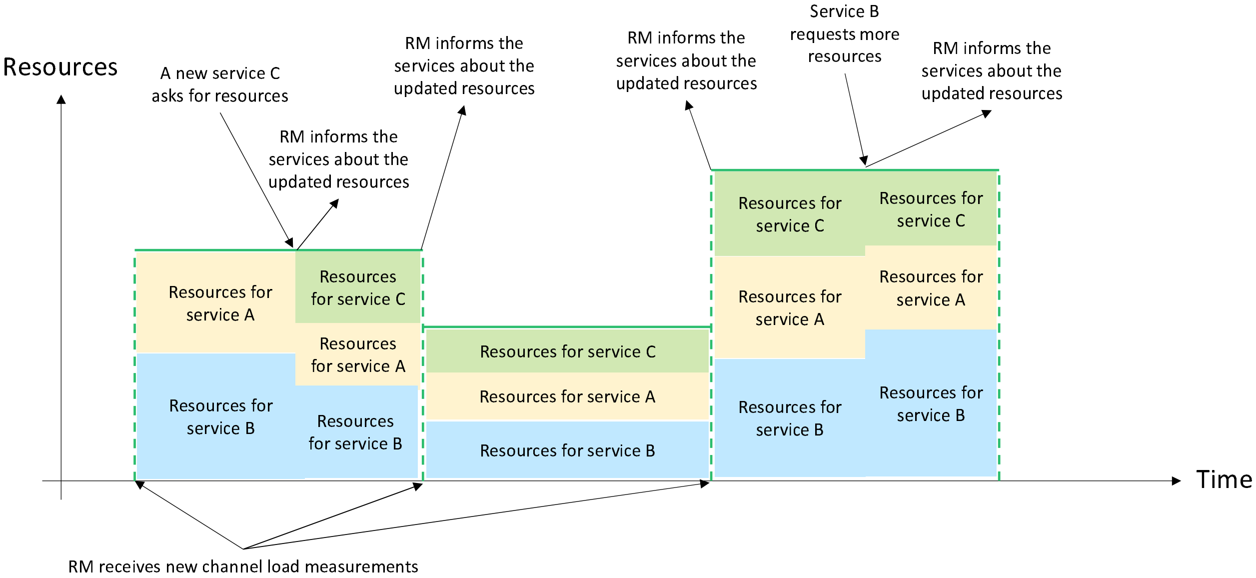


Figure 18: RM workflow with hybrid operation driven by channel load measurements and message services

A more detailed operation of the bandwidth management performed by RM is illustrated in Figure 19 for the periodic approach where RM operates according to channel load measurement cycles. As can be observed, during the first RM interval, $t = [0, \Delta T)$, there is no information yet available about the current channel load, so all message services operate in an open-loop mode - each one generating message according to its default behaviour or immediate needs. At the end of this first interval, $t = \Delta T$, the RM module obtains a new channel load measurement and collects the individual resource needs R_i from each active message service i. Based on the aggregate demand $R = \sum_i R_i$, and the channel load, RM computes the available resources for the station and for each message service, referred to as δ_i for message service i. In the second RM interval, $t = [\Delta T, 2\Delta T)$, message services adjust their message generation rates according to the assigned resources, thereby entering a closed-loop control phase. At the end of this second interval, the process is repeated: a new measurement of the channel load is taken, updated message service demands are reported, and RM recomputes the available resources for the station and for each message service.

This approach that computes the available resources for the station at the FL opens the door to handle scenarios with heterogeneous resource needs (see clause 6.4). Congestion control mechanisms such as achieving weighted-fairness [i.30] could be applied to allow that different ITS-S experiencing the same channel load have a different number of available resources depending on their message service needs.

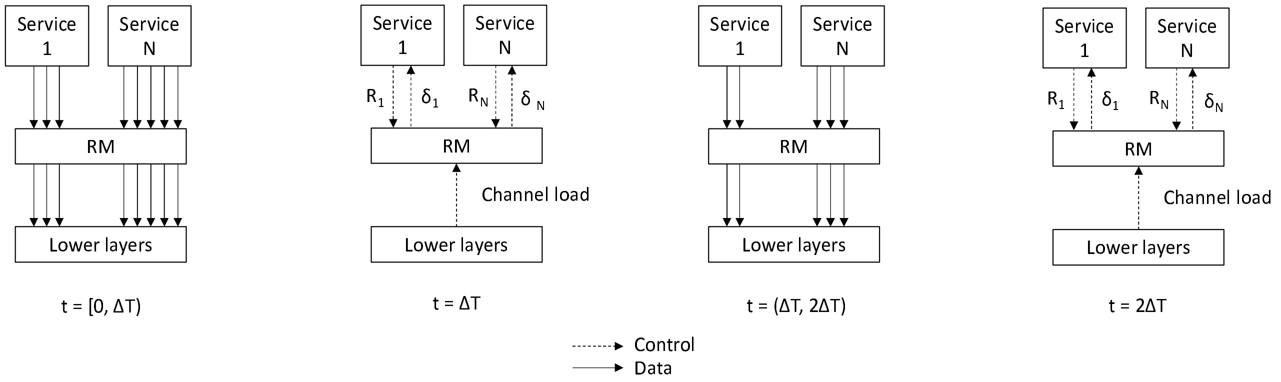


Figure 19: Interaction between RM and message services for bandwidth management with periodic operation

7.5 Resource Management approach

7.5.0 Overview

While RM can become highly complex when all functionalities are implemented in detail, a basic yet effective approach is achievable by focusing on essential requirements. The key idea is to implement a simple RM mechanism that still fulfils necessary operational and regulatory needs without the introduction of too much complexity.

At the core of a basic solution is the division of functions between two primary entities: Admission Control (AC) and Bandwidth Management. The AC serves as the initial gatekeeper by applying straightforward policies to regulate message service activation. For example, it may restrict the activation of certain message services in some regions, or the simultaneous activation of multiple message services in scenarios where their combined transmission rates might exceed system limits. This regulation ensures that certain message services are either disallowed in specific regions or managed to avoid extreme cases, such as preventing three message services disseminating at high frequencies when the overall system can only support a lower cumulative rate.

Once message services pass through AC, the Bandwidth Management is in charge of computing the resources available for the ITS-S and distributing them among the message services. In this approach, RM calculates (at FL, see clause 5.5) the resources available for the ITS-S according to the current channel load and distributes it among the active message services according to their priority and requirements. Each message service receives an allocation expressed as e.g. bits per second, which is derived from translating the computed resources and the ALI with the table discussed in clause 5.5. While a fixed ALI might be sufficient for basic implementations, more advanced setups could dynamically adjust the ALI based on factors like available bandwidth, radio access technology, or modulation and coding schemes.

In addition to Admission Control and Bandwidth Management, the RM process may include a message handling entity. In the basic solution, the system does not actively enforce traffic shaping or policing. Instead, it assumes that message services will adhere to their resource assignments and that any temporary excesses will not significantly disrupt overall performance. Continuous monitoring of resource consumption - for instance, measuring the number of bits generated by each message service in the last second - provides feedback to adjust future resource distributions.

7.5.1 RM design and implementation

The proposed RM implements a Bandwidth Management mechanism, and assumes that Admission Control simply admits all the message services implemented in the ITS-S.

The Bandwidth Management mechanism operates periodically. The process is triggered when a new CBR measurement is received from the lower layers, and is as follows:

- RM request: RM sends a message to all registered message services asking for their requirements.
- Service replies: Each message service responds with the resources it needs, defined in bits/s. Each message service estimates its requirements over the last second.

- Computation: RM computes the maximum allowed resources for each message service based on the requirements and measured CBR. RM computes the maximum allowed resources as a proportion (δ).

Algorithms inside the Bandwidth Management mechanism include:

- Computation of available resources at the station: based on the Adaptive DCC approach discussed and analysed in clause 5. Two different solutions are evaluated:
    - Adaptive DCC.
    - Adaptive DCC with adaptive beta.
- Distribution of resources: the available resources are distributed among the message services based on the concept of proportional fairness. Under this concept, message services with the same priority level receive resources in proportion to their requirements. Resource distribution follows a tiered process, beginning with the highest priority message services. If any resources remain, they are assigned to lower priority message services. When the available resources can only cover a certain percentage of the overall demand for message services of a given priority, each message service is allocated the same percentage of its requested data rate.

7.5.2 Simulation scenario and settings

The scenario considered is a static 1-hop scenario with 60 vehicles.

Three different generic message services are considered following 3GPP guidelines:

- Message service 1 corresponds to a low-load periodic traffic model. Packets are generated every 100 ms, following a predefined pattern of packet sizes: {300 bytes, 190 bytes, 190 bytes, 190 bytes, 190 bytes}. Each vehicle starts at a random point of this sequence, which ensures variability across vehicles. The resulting average data rate is low, around 17 kbps. This message service represents lightweight periodic traffic, typical of applications that transmit small amounts of information regularly.
- Message service 2 is based on a high-load periodic traffic model. The inter-packet arrival time is much shorter (10 ms), which significantly increases the data rate compared to message service 1. The packet size varies between 1 200 bytes (with probability 0,2) and 800 bytes (with probability 0,8), yielding an average throughput of approximately 272 kbps. This message service emulates applications with steady and more demanding traffic generation, where both packet size and frequency are larger than in message service 1.
- Message service 3 represents an aperiodic medium-load traffic model, introducing variability in the message generation process. The inter-packet arrival time is defined as 50 ms plus an exponentially distributed random variable with a mean of 50 ms, which results in irregular message intervals. Packet sizes are uniformly distributed between 200 and 2 000 bytes, with a quantization step of 200 bytes. The average data rate is about 56 kbps. This message service mimics traffic generated by applications with event-driven or perception-related dynamics, where both packet size and message interval may fluctuate.

All the message services have the same priority. Each message service adapts messages as instructed by RM:

- Message service 1 adapts message interval.
- Message service 2 adapts message size.
- Message service 3 adapts both interval and size.

Three vehicle types are considered in the scenario:

- Vehicles of Type 1 implement message service 1.
- Vehicles of Type 2 implement message services 1 and 2.
- Vehicles of Type 3 implement message services 1, 2 and 3.

In the scenario considered, the vehicle types are evenly distributed, with one third of the vehicles belonging to each type. Within each vehicle type, the message services generate packets asynchronously.

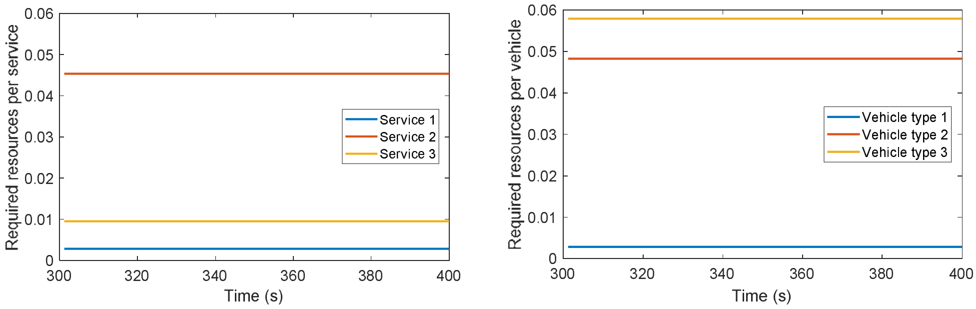
The CBR is measured by each vehicle asynchronously and periodically every 100 ms as the sum of the proportion of time that the channel is busy (received signal higher than a threshold) and the proportion of time used for transmission.

All vehicles run RM at the FL with ITS-G5 at the lower layers with a default data rate of 6 Mbps. Simulations were conducted using INET Framework with Veins over OMNeT++.

7.5.3 Results

7.5.3.0 Overview

This study starts with the analysis of the time evolution of the requirements of each message service (Figure 20(a)) and each vehicle type (Figure 20(b)). The requirements are computed by each vehicle per message service based on the last second and normalized by the default data rate. The measurements of required resources revealed the differences among the three vehicle types considered. Vehicles of Type 1, implementing only message service 1, demanded the lowest amount of resources, while vehicles of Type 2, running message services 1 and 2, exhibited intermediate requirements. Finally, vehicles of Type 3, implementing all three message services, were characterized by the highest demands. These disparities were consistent with the design of the message services, where message service 1 generated a low traffic load, message service 2 a medium one, and message service 3 added further aperiodic traffic.



(a) (b)

Figure 20: Average time evolution of the message service and vehicle requirements

7.5.3.1 Adaptive DCC

This clause presents the results obtained considering the default configuration of Adaptive DCC for the computation of available resources at the station.

Figure 21 illustrates the time evolution of the CBR measured by the vehicles in the considered scenario. The figure differentiates the median, as well as the 5th, 25th, 75th and 95th percentiles. The results show that the RM mechanism achieved the expected behaviour of stability and convergence, without significant difference among vehicles in the scenario.

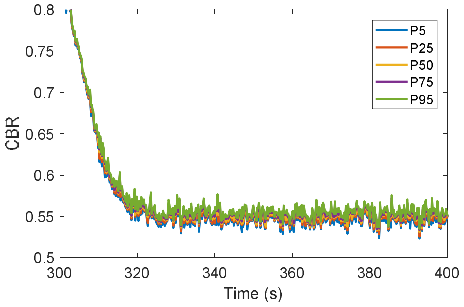


Figure 21: Time evolution of the CBR (median and different percentiles)

The evaluation of the maximum allowed resources per ITS-S, expressed through the delta (δ), showed that all vehicle types ended up being assigned the same value, despite their very different requirements (shown in Figure 20(b)). In practice, this means that each vehicle was assigned the same share of resources, regardless of whether it implemented one, two, or three message services. This uniform distribution is a direct consequence of the use of the Adaptive DCC solution that computes delta only based on the CBR, i.e. without considering the message service requirements.

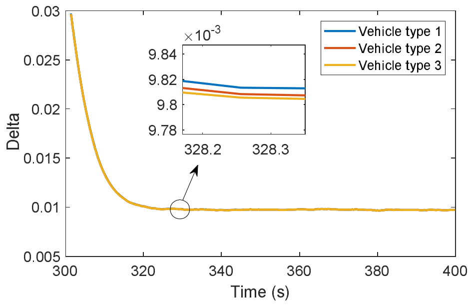
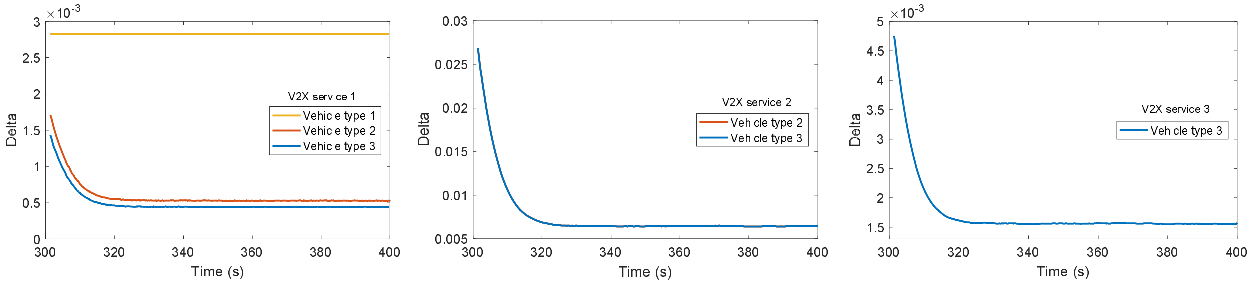


Figure 22: Time evolution of the average delta computed per vehicle type

As a result, the actual resource usage reflected these limitations, as illustrated in Figure 23. Type 1 vehicles, having modest requirements, were able to satisfy their message service demands fully with the allocated share. In contrast, Type 2 vehicles had to proportionally reduce the resources devoted to message services 1 and 2, while Type 3 vehicles faced even stronger reductions across all three message services. This behaviour confirmed that, although the RM ensured fairness at the station level, it did not account for the heterogeneous requirements introduced by different message service sets.



(a) message service 1 (b) message service 2 (c) message service 3

Figure 23: Time evolution of the average resources assigned per message service and vehicle type

In summary, the results of the one-hop scenario highlighted the limitations of the baseline RM design: even though it guaranteed stability and convergence, it allocated identical resources to all vehicles, leading to disproportionate reductions for those with higher demands. This finding motivates the need for re-designs that explicitly take into account the heterogeneity of message service requirements across stations, which are presented in clause 7.5.3.2.

7.5.3.2 Adaptive DCC with dynamic beta

In order to overcome the limitations observed in the previous clause, where all vehicles were assigned the same number of resources regardless of their actual demands, an adaptive beta mechanism is described and evaluated in this clause. This approach is based on the weighted LIMERIC scheme [i.30], that ensures that vehicles running the Adaptive DCC mechanism with different beta values converge to delta values proportional to those betas. In other words, if one vehicle has a beta that is twice as large as another, its steady-state delta will also be twice as large, and the same principle holds for any proportionality factor.

In this clause, RM configures its beta value proportionally to the resources it requires. In practice, this means that vehicles with higher demands dynamically increase their beta, while vehicles with lower requirements maintain smaller values. In the proposed design, the RM computes the beta parameter at every RM interval, and all vehicles should follow the same computation method to ensure consistent behaviour across the network. Backwards compatibility is guaranteed, since Release 1 stations continue to operate with a constant beta value.

A linear adaptive beta solution is introduced, where beta is computed proportionally to the resources required by each station. Formally:

$$\beta = \mathrm{BETA\_BASE} \times \frac{\mathrm{RequiredResources}}{\mathrm{DATA\_RATE\_BASE}}$$

where:

- *BETA_BASE* is the beta value used by Release 1 vehicles using Adaptive DCC.
- *DATA_RATE_BASE* corresponds to the average resources required by Release 1 vehicles using Adaptive DCC.
- *RequiredResources* is the sum of the resources demanded by all message services implemented in the station.

This formulation ensures that vehicles with larger requirements obtain proportionally larger beta values. Consequently, the algorithm is expected to converge to delta values that scale with beta. This property enables the RM to allocate resources fairly among heterogeneous stations, while preserving compatibility with legacy vehicles.

The results of the considered scenario with adaptive beta showed a clear improvement in the alignment between allocated resources and actual message service requirements. The computation of beta values across vehicles confirmed that the adaptation worked as intended: vehicles of the same type exhibited similar beta values, with small deviations due to the stochastic nature of their traffic generation. These differences, however, did not compromise the overall stability of the system.

The measurement of the CBR further validated the proposed solution. Stability and convergence were preserved, as in the baseline case, but the system now converged closer to the target CBR. This improvement was associated with the larger beta values assigned to vehicles with greater needs, which allowed a more efficient utilization of the channel.

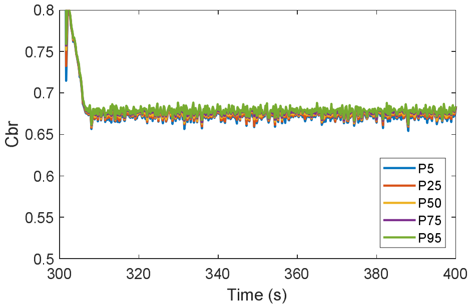


Figure 24: Time evolution of the CBR (median and different percentiles)

The maximum allowed resources per vehicle type, expressed as delta (δ), also reflected the expected behaviour, as observed in Figure 25. Unlike the previous case where all vehicles were assigned the same δ, here vehicles with higher resource requirements obtained proportionally more resources. Within each vehicle type, the δ values were nearly identical, with only small deviations, while across types, the differences were consistent with their respective Message service demands. Vehicles of Type 1, which had the lowest requirements, showed slower convergence in their δ values, an effect attributed to their reduced traffic generation and the initialization of delta to δ_{max}= 0,03.

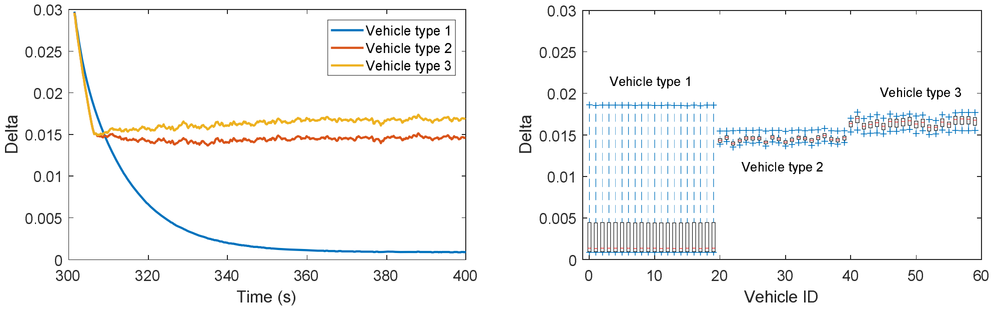
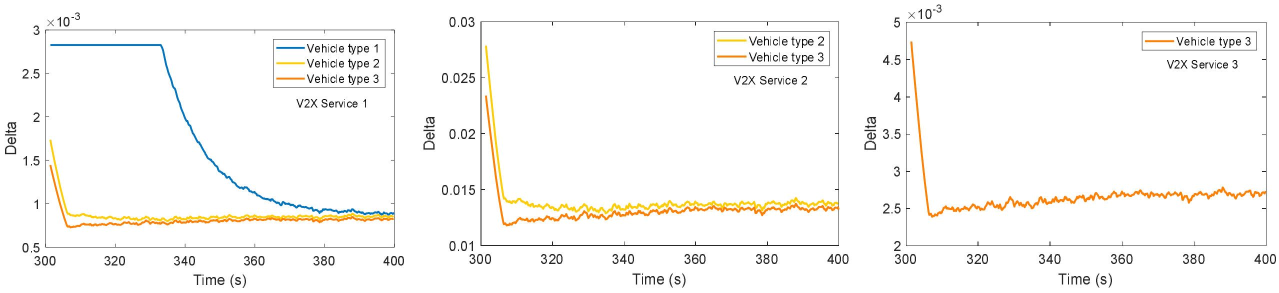


Figure 25: Time evolution and boxplots of the delta computed per vehicle type

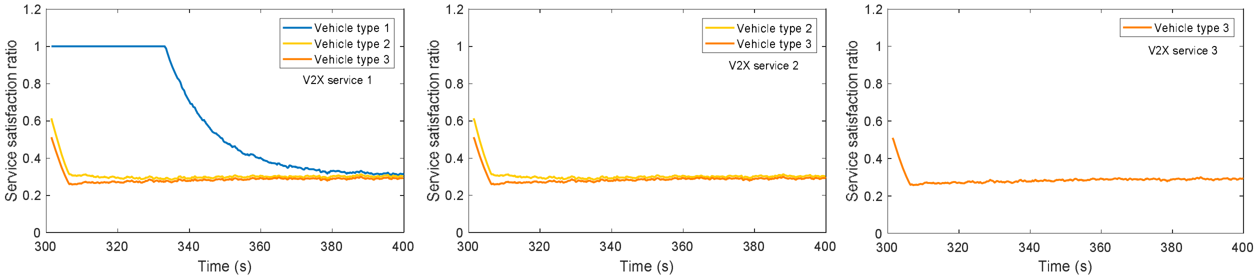
When analysing the actual usage of resources, the benefits of the adaptive beta approach can be observed in Figure 26. Vehicles of Type 2 and Type 3 adapted rapidly, reducing or maintaining their service loads in proportion to the resources allocated. Vehicles of Type 1, however, exhibited a slower adaptation process, again linked to their smaller demands and lower traffic intensity. Despite this, the system as a whole achieved a balanced allocation, i.e. all message services converge to the same delta, that better reflected the heterogeneity of the scenario.



(a) message service 1 (b) message service 2 (c) message service 3

Figure 26: Time evolution of the average resources assigned per message service and vehicle type

Finally, the evaluation of the message service satisfaction ratio - defined as the ratio between the resources assigned and the resources required - showed that all message services across all vehicle types converged towards the same value, approximately 0,29 (see Figure 27). This result demonstrates that the adaptive beta mechanism not only ensures proportional fairness across heterogeneous vehicles but also equalizes the level of satisfaction among message services, regardless of the vehicle type implementing them.



(a) message service 1 (b) message service 2 (c) message service 3

Figure 27: Time evolution of the message service satisfaction ratio per message service and vehicle type

In summary, the one-hop scenario with adaptive beta highlighted the effectiveness of the proposed re-design. By dynamically adjusting the beta values according to the actual requirements of each vehicle, the Bandwidth Management mechanism of RM was able to provide more resources to vehicles with greater needs, maintain system stability, and bring the operation closer to the CBR target. At the same time, it preserved fairness among message services by equalizing their satisfaction levels, thereby overcoming the limitations of the baseline configuration.

7.5.4 Conclusion Resource Management approach

The results demonstrate that an RM approach running at the FL based on Adaptive DCC converges properly and provides stable operation, as also shown in clause 5 and Annex C. However, when applied to scenarios with heterogeneous message services of equal priority, the approach exhibits clear limitations, since it does not fully account for the diversity of message service requirements across stations.

A promising solution would be to allow the RM to dynamically adapt the configuration of Adaptive DCC according to the resources demanded by each vehicle, thereby improving fairness and efficiency in heterogeneous deployments. Nevertheless, further investigation is required to assess the behaviour of this solution in scenarios where message services are assigned different priorities, which remains an open line of analysis.

Annex A:
Rationale for the limits imposed by congestion control

The rationale for equation (2) in clause 5.2.4, which is derived from ETSI EN 302 571 [i.16], is described in ETSI TS 103 175 [i.15] and hereafter elaborated.

The starting point is the derivation of the maximum channel occupation of the generic station, hereafter called CR_{Limit}, as a function of the overall channel load, which is measured by the CBR. The maximum channel occupation can also be written as a function of the minimum time between two consecutive transmissions where the transceiver is not allowed to generate a signal, denoted as $T_{offLimit}$ and the duration of the last transmission T_{on} as:

$$CR_{Limit} = \frac{T_{on}}{T_{on}+T_{offLimit}} \tag{A.1}$$

Since the maximum channel occupation of the generic station needs to depend on the number of stations, but this information is not explicitly available, an assumption is made on the CBR. In particular, it is assumed that the maximum CBR, denoted as CBR_{Limit}, is a function of the number of stations concurring to access the same channel in the same area, denoted as N_{sta}. This assumption is introduced to allow an implicit derivation of the number of stations directly from the measured CBR. This assumption can also be written as:

$$CBR_{Limit} = N_{sta} \times a + b \tag{A.2}$$

where a and b are two constants, and thus:

$$N_{sta} = \frac{CBR_{Limit}-b}{a} \tag{A.3}$$

Given the maximum CBR and the number of stations, the maximum channel occupation of the generic station can be calculated as:

$$CR_{Limit} = \frac{CBR_{Limit}}{N_{sta}} = \frac{CBR_{Limit}}{\left(\frac{CBR_{Limit}-b}{a}\right)} = \frac{a \times CBR_{Limit}}{CBR_{Limit}-b} \tag{A.4}$$

Using equations (A.1) and (A.4), by first writing $T_{offLimit}$ as a function of CR_{Limit} and then substituting CR_{Limit} with its expression as a function of CBR_{Limit}, resulting in:

$$T_{offLimit} = T_{on} \times \left(\frac{1-CR_{Limit}}{CR_{Limit}}\right) = T_{on} \times \left(\frac{1}{CR_{Limit}} - 1\right) = T_{on} \times \left(\frac{1}{a}\frac{CBR_{Limit}-b}{CBR_{Limit}} - 1\right) \tag{A.5}$$

The final step is that the measured CBR, indicated as CBR, is assumed equal to CBR_{Limit}, which brings to:

$$T_{offLimit} = T_{on} \times \left(\frac{1}{a}\frac{CBR-b}{CBR} - 1\right) \tag{A.6}$$

Which corresponds to equation (2) in clause 5.2.4 (and thus the limit indicated by ETSI EN 302 571 [i.16]) when $a = 1/4\,000$ and $b = 0{,}62$ are used. These two parameters were empirically determined to limit the packet collision ratio and to provide a robust feedback for deriving N_{sta} from the measured CBR.

It can be observed that the assumption that the measured CBR is equal to the limit implies that each station tends to consider the channel always congested, which may not be true. However, if the channel is not congested the effect is that the station under observation underestimates the number of contending stations and overestimates the portion of resources it can use. Given that the channel is not really congested, this may only cause an increase of the CBR until it actually reaches the level of congestion.

Annex B: Methods to characterize congestion control algorithms

B.1 Modelling of a rate control loop

B.1.1 Definition of the channel busy ratio limit

Several independent transmitters that want to share a radio channel without coordination by a central station need a mechanism that avoids data packet collisions and that takes care of the available channel resources. For simplification of the derived model of the congestion control it is assumed that data packet collisions are effectively avoided by the CSMA/CA algorithm when the radio channel is not overloaded and that the load is only controlled by the rate and duration of the data packets. This simplifies the description and makes an analytic evaluation possible. Anyhow, the congestion control is designed to avoid packet collisions by keeping the channel load reasonably low.

Obviously, all transmitters should not try to put more packets on the channel than the channel capacity allows. It is even so that the full channel capacity can only be reached at the cost of massive packet collisions (packets of different transmitters overlap in time). Most of these overlapping packets cannot be decoded in the receivers and are therefore waste of channel resources. Hence, the optimum channel load is well below the channel capacity. A congestion control should allow a system of multiple transmitters to use the channel resources up to, or close to, the optimum channel load, and avoid an operation above this load limit.

The channel resources R can be seen as percentage of the total available transmit time for all transmitting nodes ($0 < R < 1$). Whereas the channel utilization u is the percentage of the total available time each node can transmit. Assuming that all nodes N share the available resources equally, u can be found by dividing R by N (equation (B.1)):

$$u = \frac{R}{N} \tag{B.1}$$

When the channel load is the only input parameter to the control algorithm, the transmitters do not know the number of other transmitters contributing to the channel load, and the distribution of the channel load cannot be done by just dividing the available resources by the number of nodes. The control algorithm can only inherently divide the resources equally from only knowing the channel load. This is possible when the channel load has a one-to-one relation to the number of nodes.

ETSI specifies in ETSI TS 103 175 [i.15] a linear relation between the channel load limit and the number of contributing nodes (see also Annex A and equation (B.2)):

$$CBR_{Limit} = N \times a + b \tag{B.2}$$

Where CBR_{Limit} is the upper channel busy ratio limit that should not be exceeded by the measured channel load CL and a and b are parameters. An example for $a = 1/4\,000$ and $b = 0{,}62$ based on ETSI EN 303 797 [i.32] is shown in Figure B.1.

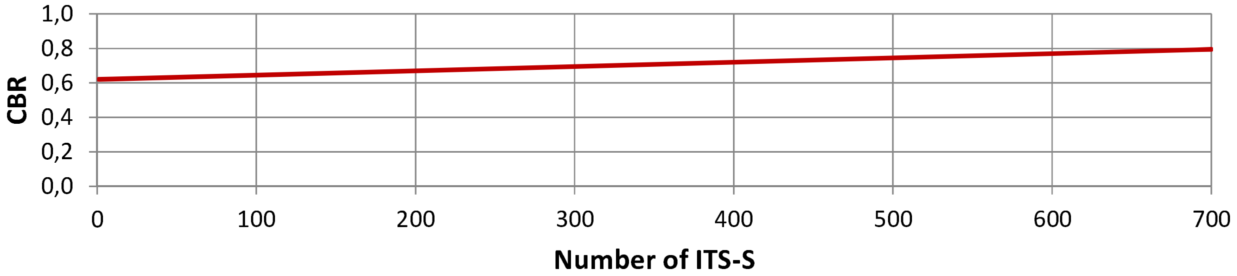


Figure B.1: Example of a CBR limit according to equation (B.2)

The measured channel load results from the sum of the channel utilizations u of all nodes (equation (B.3)):

$$CL = \sum_{k=1}^{N} u_k \tag{B.3}$$

Figure B.2 shows the contribution of each rate controller to the channel load. Other types of congestion control are not considered in the present document since they are less effective and more complicated to implement.

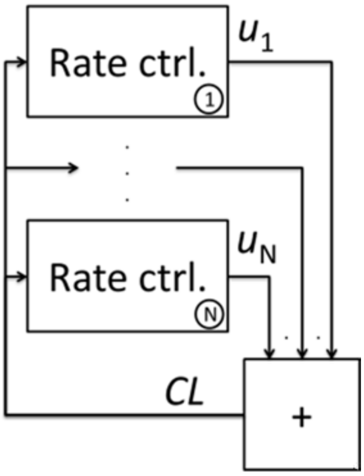


Figure B.2: Contribution of each rate control to the channel load

When all rate controllers are the same, all channel utilizations u_k are equal to u and the resulting channel load CL is given by equation (B.4):

$$CL = N \times u \tag{B.4}$$

When these equal rate controllers are working properly and equilibrium is reached, all u_k are equal $\tilde{u}$ and the resulting steady state channel load $\widetilde{CL}$ is given by equation (B.5):

$$\widetilde{CL} = N \times \tilde{u} \tag{B.5}$$

B.1.2 Function of the rate controller

The channel utilization u of each node is controlled by adjusting the time T_{off} in between two transmitted packages according to the given duration T_{on} of the package (equation B.6), so that the resulting utilization u does not exceed the limit U_{max} given by (equation (B.7) and equation (B.8)):

$$u = \frac{T_{on}}{T_{on}+T_{off}} \tag{B.6}$$

$$U_{max} = \frac{CBR_{Limit}}{N} \tag{B.7}$$

$$u \leq U_{max} \tag{B.8}$$

Hence, the rate controller is working in discrete time steps with a variable length of $T_{off} + T_{on}$.

The number of nodes N is unknown to each node, but an upper bound for the number of nodes N_{est} can be estimated from the measured channel load CL when assuming that $CL \leq CBR_{\text{Limit}}$ and by substituting CBR_{Limit} by CL in equation (B.2). Since CL can be smaller than b, the minimum number of estimated nodes N_{est} is fixed to at least one in equation (B.9):

$$N_{est} = max\left(1; \frac{CL-b}{a}\right) \tag{B.9}$$

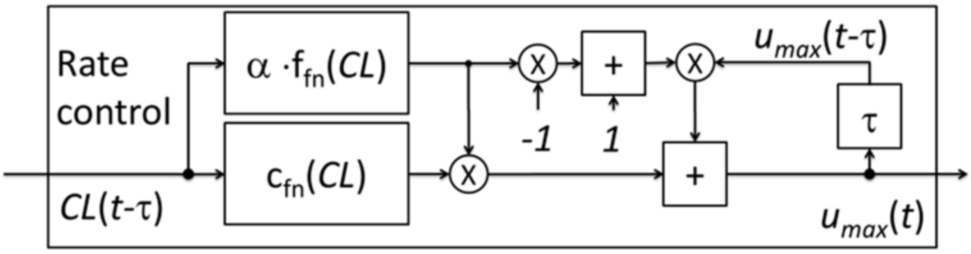
From this a lower bound of U_{max} can be calculated by use of equation (B.7) and equation (B.2) when substituting N with N_{est} (see equation (B.10)):

$$U_{max} = \frac{N_{est} \cdot a+b}{N_{est}} \tag{B.10}$$

The distributed rate controllers are not synchronized and therefore the measurement period τ for the channel load determination should be long enough. Either 100 ms or a duration of $T_{off} + T_{on}$ are considered. Also, a dissemination of the CL values between the nodes can be foreseen to increase the robustness of the measurement.

B.1.3 Structure of a feedback controller

Figure B.3 shows a common basic structure how a discrete time rate control in each node can be implemented. The channel load $CL(t\text{-}\tau)$ measured in the previous time step at $t\text{-}\tau$ and the previous dynamic upper bound of the channel utilization $u_{max}(t\text{-}\tau)$ is used by the control function $\mathrm{c_{fn}}$ and the filter function $\alpha \times \mathrm{f_{fn}}$ to determine the next dynamic channel utilization limit $u_{max}(t)$.



NOTE: The filter function $\mathrm{f_{fn}}$ might not be used, and even the factor α is set to one in most implementations.

Figure B.3: Block diagram of the rate control

Equation (B.11) relates to the rate controller shown in Figure B.3 and results in the dynamic channel utilization limit $u_{max}(t)$:

$$u_{max}(t) = \alpha \times \mathrm{f_{fn}}\big(CL(t-\tau)\big) \times \mathrm{c_{fn}}\big(CL(t-\tau)\big) + \Big(1 - \alpha \times \mathrm{f_{fn}}\big(CL(t-\tau)\big)\Big) \times u_{max}(t-\tau) \qquad \text{(B.11)}$$

When no filtering to the input signal $CL(t\text{-}\tau)$ is used in the controller, the filter function is constant and equal to one ($\alpha \times \mathrm{f_{fn}} = 1$). In this case the dynamic channel utilization $u_{max}(t)$ is just given by the control function $\mathrm{c_{fn}}(CL(t\text{-}\tau)) = u_{max}(t)$. This type of controller implementation is the simplest one, but it is prone to instabilities, since the stability and the control equilibrium are both given by the control function. Using a filtering function that differs from one ($\alpha \times \mathrm{f_{fn}} \neq 1$), offers the possibility to decouple the control equilibrium from the controller stability as will be shown in clause B.2.

B.2 Control equilibrium

The control equilibrium for a control function $\mathrm{f_{fn}}$ is the steady state channel load $CL(t\text{-}\tau) = CL(t) = CL$ produced by a given number of nodes N that are all utilizing the channel with the same constant $u_{max} = u_1 = u_2 = \ldots = u_N = U_{max}$. For the steady state equilibrium equation (B.11) simplifies to equation (B.12):

$$U_{max} = \alpha \times \mathrm{f_{fn}}(CL) \times \mathrm{c_{fn}}(CL) + \big(1 - \alpha \times \mathrm{f_{fn}}(CL)\big) \times U_{max} \qquad \text{(B.12)}$$

From equation B.12 the channel utilization limit U_{max} as function of the channel load CL can be determined:

$$U_{max} = \mathrm{c_{fn}}(CL) \qquad \text{(B.13)}$$

Equation (B.13) shows that the filter function $\alpha \times \mathrm{f_{fn}}$ has no influence on the control equilibrium CL and on the steady state channel utilization U_{max}. Only the control function $\mathrm{c_{fn}}$ determines the steady state characteristics of the controller shown in Figure B.3.

Clause B.3 and clause B.4 will show that the controller stability and the controller dynamics are not only influenced by the control function $\mathrm{c_{fn}}$ but also by filter function $\alpha \times \mathrm{f_{fn}}$.

Finally, when substituting $U_{max}=u$ into equation (B.4), the steady state control equilibrium $\widetilde{CL}$ can be calculated from the control function $\mathrm{c_{fn}}$ for a given number of nodes N when solving equation (B.14) for $\widetilde{CL}$:

$$\widetilde{CL} = N \times \mathrm{c_{fn}}\big(\widetilde{CL}\big) \qquad \text{(B.14)}$$

B.3 Stability

B.3.1 Different types of stability

Congestion control algorithms are implemented as discrete-time controllers. That means that they will change the control value (channel utilization u) not at any arbitrary point in time, but only after discrete time intervals τ. This implies that a stability evaluation cannot be done by inspecting the continuous time differential equation of the control loop alone. In addition, discrete time oscillations, caused by too long intervals τ, need to be studied.

Controller stability is given when within a given range of node numbers N the control loop converges independently of the initial channel load $CL(t_0)$ to a channel load $CL(t)$ that is bounded within a defined small range (bounded stability). Such a bounded stability criteria is necessary to account for quantization steps in time and channel utilization.

B.3.2 Description of the controller by a differential equation

To analyse the dynamic behaviour of the distributed controllers the discrete time control equation (B.11) is converted into the differential equation (B.17). This is done in a first step by dividing equation (B.11) by the discrete time step size τ and rewriting it in such way that the difference equation (B.15) is obtained.

The left side of equation (B.15) is the ratio between the utilization difference $\Delta u_{max} = u_{max}(t)\text{-}u_{max}(t\text{-}\tau)$ and the time difference $\Delta t = \tau$ between $u_{max}(t)$ and $u_{max}(t\text{-}\tau)$. When additionally substituting $t\text{-}\tau$ by $t\text{-}\Delta t$ on the right side of equation (B.15), equation (B.16) is obtained.

Under the assumption that the control function $\mathrm{c_{fn}}$ and the filtering function $\mathrm{f_{fn}}$ are both analytic, the difference equation (B.16) can be converted by a limiting process into the differential equation (B.17). Where $u(t)$ is the continuous time function corresponding to the discrete time function $u_{max}(t)$:

$$\frac{u_{max}(t)-u_{max}(t-\tau)}{\tau} = \frac{\alpha\times \mathrm{f_{fn}}\big(CL(t-\tau)\big)}{\tau} \times \Big(\mathrm{c_{fn}}\big(CL(t-\tau)\big) - u_{max}(t-\tau)\Big) \tag{B.15}$$

$$\frac{\Delta u_{max}}{\Delta t} = \frac{\alpha\times \mathrm{f_{fn}}\big(CL(t-\Delta t)\big)}{\tau} \times \Big(\mathrm{c_{fn}}\big(CL(t-\Delta t)\big) - u_{max}(t-\Delta t)\Big)\Big|\lim_{\Delta t\to 0} \tag{B.16}$$

$$u' = \frac{du}{dt} = \frac{\alpha\times \mathrm{f_{fn}}\big(CL(t)\big)}{\tau} \times \big(\mathrm{c_{fn}}\big(CL(t)\big) - u(t)\big) \tag{B.17}$$

For N identical controllers, the time behaviour of the channel utilization $u(t)$ as function of the number of nodes N results from solving differential equation (B.18):

$$u' = \frac{\alpha\times \mathrm{f_{fn}}(N\times u)}{\tau} \times (\mathrm{c_{fn}}(N\times u) - u) \tag{B.18}$$

By use of equation (B.4) also the time behaviour of the channel load $CL(t)$ can be obtained from equation (B.18).

B.3.3 Convergence

Even when equation (B.14) has a solution for the equilibrium channel load $\widetilde{CL}$ that lies within 0 and 1 as given by the definition of the channel load, the controller might not converge to this equilibrium. This can be the case when the slope of the control characteristic is not monotonic towards the point of equilibrium. This could be caused by an ill formed control function with ripples in the slope, or when equation (B.14) has more than one solution for $\widetilde{CL}$.

For convergence following criteria based on equation (B.16) should be met:

$$(\mathrm{c_{fn}}(N\times u) - u < 0 \text{ for } 1 > u > \tilde{u}) \text{ and } (\mathrm{c_{fn}}(N\times u) - u > 0 \text{ for } 0 < u < \tilde{u}) \tag{B.19}$$

Where $\tilde{u}$ is the controller equilibrium as calculated from equation (B.5) an equation (B.14).

B.3.4 Continuous-time stability

The convergence criteria given by equation (B.19) are not sufficient to guarantee a stable control loop. Only when in addition the solution of differential equation (B.18) shows at least a decaying oscillation, or even no oscillation, for the channel utilization $u(t)$ within a given range of node numbers N and for all starting values $0<u(t_0)<1$, the continuous-time control loop is stable for this range of N.

B.3.5 Discrete-time Stability

Since the congestion control is implemented as controller that measures the channel load CL and changes the channel utilization u_{max} repeatedly after discrete-time intervals τ, the continuous-time stability as given in clause B.3.4 is a necessary, but not sufficient criteria for the stability of the control loop.

When the continuous time solution converges for all stations to the same stable value $\tilde{u}$ (see equation (B.5)), the discrete-time controller can be unstable when $u(t)$ changes in one time step within an interval of τ by at least twice the distance to $\tilde{u}$ (overshoot). The $u(t)$ change over one time step with a duration of τ equals $u'(t) \times \tau$. Where $u'(t)$ is the slope of the $u(t)$ function at the time t. From this, the discrete time realization for a controller that overshoots $\tilde{u}$ is stable when equation (B.20) is fulfilled for all $t \geq 0$ within a given range of node numbers N and for all starting values $0 < u(t_0) < 1$:

$$\tau \times |u'(t)| < 2 \times |\tilde{u} - u(t)| \tag{B.20}$$

This implies that a discrete time controller is also stable when the channel utilization does not overshoot the controller equilibrium $\tilde{u}$ as expressed by equation B.21. When equation B.21 is met, the controller shows a favourable behaviour without discrete time oscillations:

$$\tau \times |u'(t)| \leq |\tilde{u} - u(t)| \tag{B.21}$$

Since τ is always positive, equation (B.20) and equation (B.18) can be combined to form the discrete-time stability criterium given in equation (B.22):

$$\left|\alpha \times \mathrm{f_{fn}}\big(N \times u(t)\big) \times \Big(\mathrm{c_{fn}}\big(N \times u(t)\big) - u(t)\Big)\right| < 2 \times |\tilde{u} - u(t)| \tag{B.22}$$

This criterium is a function of the channel utilization $u(t)$ and the node number N. It should be fulfilled within the whole range of $0 < u(t) < 1$ and within the given range of node numbers N where the controller should be stable.

B.4 Control dynamics

The convergence speed of the controller can be characterized with a channel load step function. Since the equilibrium might not be exactly reached because of quantization effects and measurement noise, a definition of the convergence speed by the time until a certain percentage of the channel load equilibrium is reached can be used. In addition, it makes sense to characterize the decay time of the controller oscillations, since it can be much longer that the time the channel utilization reaches a certain percentage of the equilibrium. Another criterium to characterize the control dynamics is the overshoot and undershoot relative to the equilibrium channel utilization when a channel load step function is applied. Also, the step size of the channel utilization quantization is an important parameter when defining the bounded stability criteria.

To get a first impression of the convergence speed and the decay time of the controller oscillations an inspection of the result of the continuous time differential equation (B.18) is helpful. But this result is just a guide value for the discrete time controller as given by equation (B.11). The discrete time implementation can converge even faster than the continuous time controller when $\tau \times |u'(t)| = |\tilde{u} - u(t)|$, or much slower when only equation (B.22) is fulfilled.

The control dynamics of the discrete time controller can be calculated iteratively from equation (B.11). Only for very simple control functions $\mathrm{c_{fn}}$ and filtering functions $\mathrm{f_{fn}}$ exact closed form analytic solutions are possible for the dynamics of a discrete time controller.

Annex C:
Characterization of congestion control algorithms

C.1 Reactive congestion control

C.1.1 Control equilibrium of the reactive congestion control

The reactive congestion control algorithm is based on a control function for T_{off} (equation (C.1)):

$$T_{off}(t) = CBR(t - \tau) \times T_a + T_b \tag{C.1}$$

Where T_a and T_b are parameters and the channel busy ratio *CBR* is the measured channel load. This implies that the equilibrium channel load *CL* is not only depending on the number of nodes *N*, but also on the duration of the transmissions T_{on}. This follows from equation (B.4) and equation (B.6) when assuming that *CL* is equal *CBR* (*CL* = *CBR*):

$$CL = N \times \frac{T_{on}}{T_{on} + T_{off}} \tag{C.2}$$

When combining equation (C.1) with equation (C.2) the T_{off} control function can be rewritten to:

$$T_{off}(t) = N \times \frac{T_{on}(t-\tau)}{T_{on}(t-\tau) + T_{off}(t-\tau)} \times T_a + T_b \tag{C.3}$$

To simplify the calculation, it is assumed that all nodes use the same time independent T_{on} = const. With this assumption and based on equation (C.3) the equilibrium $\tilde{T}_{off}$ can be calculated from equation (C.4):

$$\tilde{T}_{off} = N \times \frac{T_{on}}{T_{on} + \tilde{T}_{off}} \times T_a + T_b \tag{C.4}$$

What leads to a quadratic equation for $\tilde{T}_{off}$:

$$\tilde{T}_{off}^2 + \tilde{T}_{off} \times (T_{on} - T_b) - T_{on} \times (T_b + N \times T_a) = 0 \tag{C.5}$$

Equation (C.5) has following two solutions for $\tilde{T}_{off}$:

$$\tilde{T}_{off}\Big|_2^1 = \frac{1}{2}\left((T_b - T_{on}) \pm \sqrt{(T_{on} + T_b)^2 + 4 \times T_{on} \times N \times T_a}\right) \tag{C.6}$$

The channel load equilibrium $\widetilde{CL}$ results from equation (C.2) when substituting T_{off} by $\tilde{T}_{off}$ obtained from equation (C.6).

$$\widetilde{CL}\Big|_2^1 = \frac{2 \times N \times T_{on}}{T_b + T_{on} \pm \sqrt{(T_{on} + T_b)^2 + 4 \times T_{on} \times N \times T_a}} \tag{C.7}$$

As a result of the quadratic equation (C.5) there are two channel load equilibrium $\widetilde{CL}$ solutions given by equation (C.7). For the control stability this requires that only one $\widetilde{CL}$ solution lies within the channel load boundaries of $0 < CL < 1$ and an analysis of the convergence within this channel load range is necessary.

As an example, from Table A.1 and Table A.2 in ETSI TS 102 687 [i.14] the parameters T_a and T_b that fit best to the table entries can be calculated by a linear regression as shown in Figure C.1 and Figure C.2. The results are listed in Table C.1.

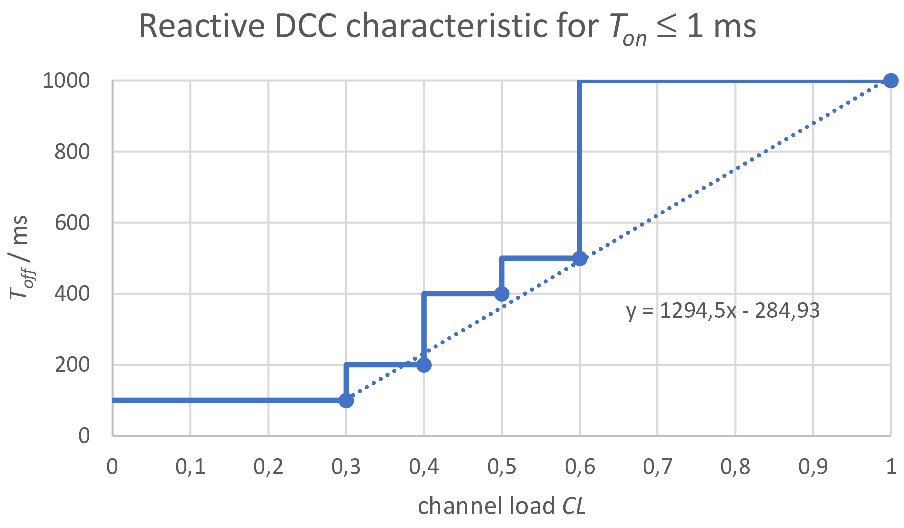


Figure C.1: Linear regression of the DCC function given in Table A.1 of ETSI TS 102 687 [i.14]

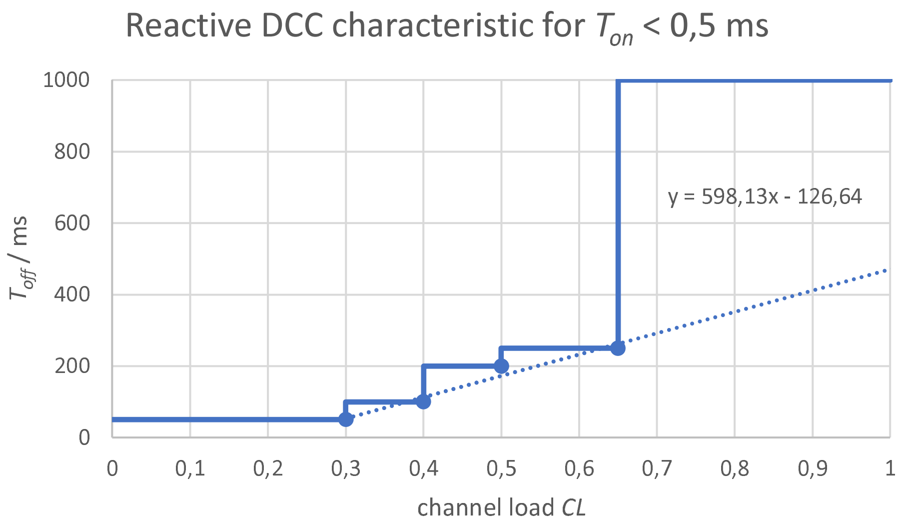


Figure C.2: Linear regression of the DCC function given in Table A.2 of ETSI TS 102 687 [i.14]

Table C.1: Parameters T_a and T_b derived from ETSI TS 102 687 [i.14]

Parameter	$T_{on} < 0,5$ ms	$0,5 \text{ ms} \leq T_{on} \leq 1$ ms
T_a	598 ms	1 295 ms
T_b	-127 ms	-285 ms

Figure C.3 and Figure C.4 show the positive channel load equilibria calculated from equation (C.7) as function of the node number N and the parameters given in Table C.1. The dashed lines show the results outside the T_{on} range to show that these results either over utilize or underutilize the channel for large node numbers. The dotted line is the CBR limit for the example based on ETSI EN 303 797 [i.32] shown in Figure C.3.

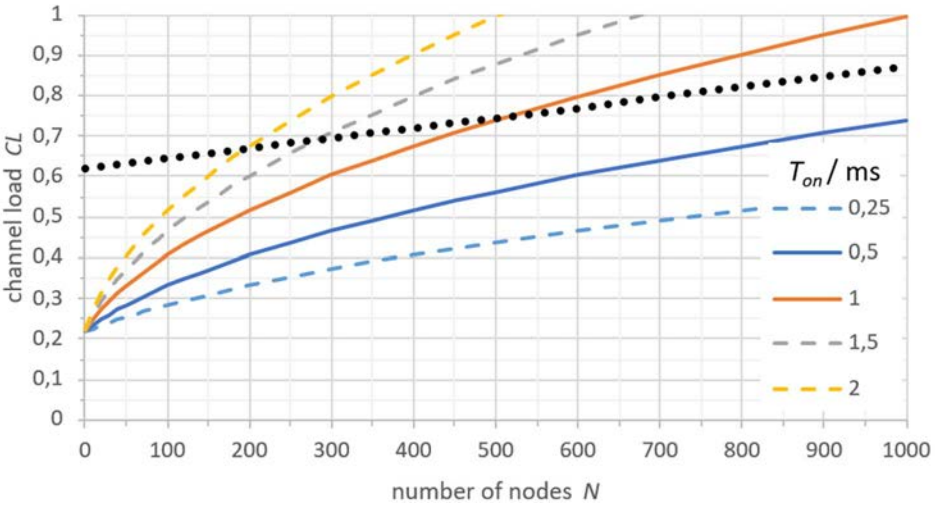


Figure C.3: Equilibrium channel load of reactive congestion control for T_a and T_b from Table C.1 for 0,5 ms <T_{on} ≤ 1 ms

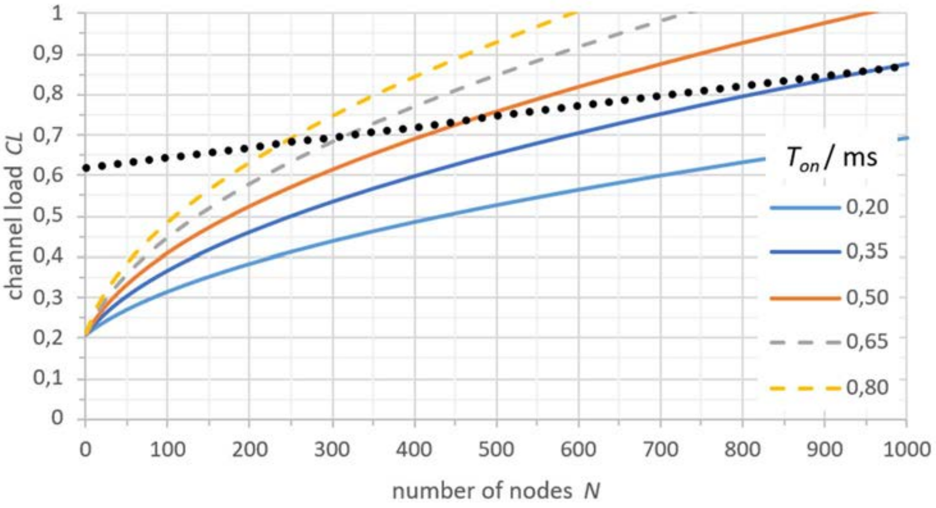


Figure C.4: Equilibrium channel load of reactive congestion control for T_a and T_b from Table C.1 for T_{on} ≤ 0,5 ms

C.1.2 Convergence of the reactive congestion control

To analyse the convergence, the channel load control function c_{fn} of the reactive controller is be determined by first substituting equation (C.1) in equation (C.2) under the assumption that *CL=CBR*:

$$CL = N \times \frac{T_{on}}{T_{on} + CL \times T_a + T_b} \qquad \text{(C.8)}$$

With the help of equation (B.14) the channel load control function c_{fn} can be found from equation (C.8):

$$c_{\mathrm{fn}}(CL) = \frac{T_{on}}{CL \times T_a + T_b + T_{on}} \qquad \text{(C.9)}$$

To check the convergence criteria given by equation (B.19), the channel load control function c_{fn} (equation (C.9)) is used:

$$\left(\frac{T_{on}}{N \times u \times T_a + T_b + T_{on}} - u < 0 \text{ for } 1 > u > \tilde{u}|_2^1\right) \text{ and } \left(\frac{T_{on}}{N \times u \times T_a + T_b + T_{on}} - u > 0 \text{ for } 0 < u < \tilde{u}|_2^1\right) \qquad \text{(C.10)}$$

Where $\tilde{u}|_2^1$ represents the solution of the equilibrium channel utilization that is within the allowed range of $0 < \tilde{u} < 1$ obtained from equation (B.5) and equation (C.7). In case equation (C.7) has two solutions within this range, convergence is only given when the range of u is limited in such a way that only one solution is within this range and equation (C.10) is fulfilled there.

Or in terms of CL equation (C.10) can be written as equation (C.11):

$$\left(\mathrm{c_{fn}}(CL) - CL < 0 \text{ for } 1 > CL > \widetilde{CL}\Big|_2^1\right) \text{ and } \left(\mathrm{c_{fn}}(CL) - CL > 0 \text{ for } 0 < CL < \widetilde{CL}\Big|_2^1\right) \qquad \text{(C.11)}$$

When applying the convergence criteria to the examples based on ETSI TS 102 687 [i.14] given in in Table C.1 it can be seen form Figure C.5 and Figure C.6 that the reactive congestion control will converge to the negative equilibrium when *CL* is somewhere below 0,2. The correct convergence area above a *CL* of around 0,2 to the positive *CL* equilibrium is highlighted in green, the wrong convergence to the negative *CL* equilibrium is marked in red, and the negative (impossible) *CL* area is marked in white. This is the reason why this control algorithm needs to be implemented by a table that has no entries below a *CL* of 0,3 to avoid a convergence to the impossible negative *CL* equilibrium.

The convergence direction is given by $\mathrm{c_{fn}}(CL)$ which has a pole when $CL \times T_a + T_b + T_{on}$ gets zero. Since T_a and T_{on} are always positive, a pole for a positive *CL* can only happen when T_b is negative. For the example given in in Table C.1 and when assuming that the T_{on} values are below 2 ms the pole is at a $CL = (285\ ms - T_{on})/1\,295\ ms \approx 0{,}22$ or at a $CL = (127\ ms - T_{on})/598\ ms \approx 0{,}21$ as shown in Figure C.5 and Figure C.6.

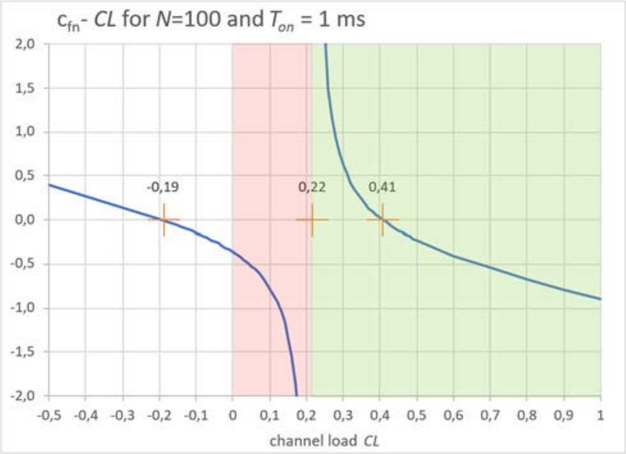


Figure C.5: Convergence criteria function for *N* = 100, T_{on} = 1 ms, and the parameters given in Table C.1

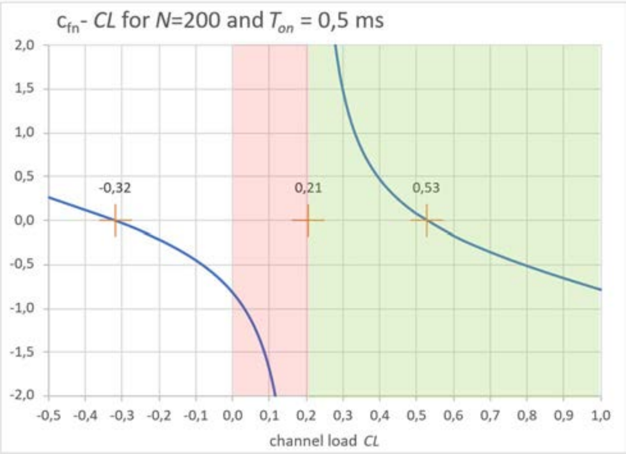


Figure C.6: Convergence criteria function for *N* = 100, T_{on} = 0,5 ms, and the parameters given in Table C.1

C.1.3 Stability of the reactive congestion control

C.1.3.1 Stability of the reactive congestion control without filtering according to ETSI TS 102 687

C.1.3.1.1 Continuous time stability

According to clause B.1.3 the control equation without filtering for a reactive congestion control is:

$$u_{max}(t) = \frac{T_{on}}{CL(t-\tau) \times T_a + T_b + T_{on}} \qquad \text{(C.12)}$$

Equation (C.12) leads with equation (B.17) and equation (B.4) to differential equation (C.13) hat can be solved by separation of the variables:

$$\frac{dCL}{dt} = \frac{1}{\tau} \times \left(\frac{N\times T_{on}}{CL\times T_a + T_b + T_{on}} - CL\right) \qquad \text{(C.13)}$$

$$\tau \times \int \frac{1}{\left(\frac{N\times T_{on}}{CL\times T_a + T_b + T_{on}} - CL\right)} dCL = \int 1 \, dt \qquad \text{(C.14)}$$

After some calculations this leads to a solution for t in relation to the step size τ given by equation (C.15):

$$\frac{t+T_0}{\tau} = -\frac{1}{2} \times \left(\log(T_a \times CL^2 + B \times CL - N \times T_{\text{on}}) - \frac{B}{A} \times \log\left(\frac{2\times CL\times T_a + B - A}{2\times CL\times T_a + B + A}\right)\right) \qquad \text{(C.15)}$$

Where T_0 is an integration constant to adjust the time offset and A and B are constants given by:

$$\sqrt{{T_{\text{on}}}^2 + (2 \times T_b + 4 \times N \times T_a) \times T_{\text{on}} + {T_b}^2} = A \text{ and } T_b + T_{on} = B \qquad \text{(C.16)}$$

The solution of the differential equation shows no oscillating term. Together with the convergence criteria and the initial value, this defines a parameter range and boundary conditions where a stable convergence to the control equilibrium of the continuous time reactive congestion control algorithm can be granted analytically.

Figure C.7 shows in red the solution given by equation (C.15) for $N = 100$, $T_{on} = 1$ ms, and the parameters given in Table C.1. Where the offset T_0 was adjusted so that the time t is zero for a channel load CL equal to one. The blue crosses show a numerical solution starting at a CL of one. The step size for this numeric solution is $\tau/50$. With this small step size, the difference to the analytic solution is neglectable. Furthermore, the analytic solution shows for a CL below 0,22 that the CL converges with increasing time t to decreasing channel load CL values and does not reach the positive equilibrium at $CL = 0{,}405$ as also shown in Figure C.5.

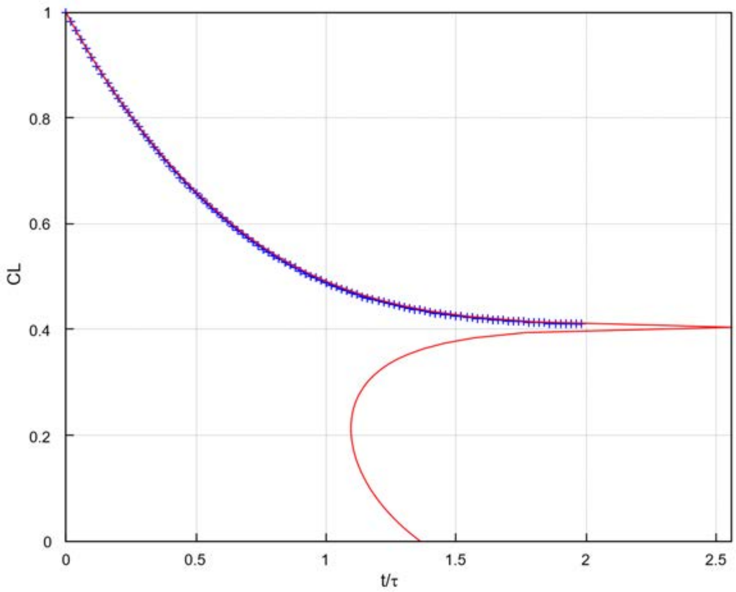


Figure C.7: Analytic and numeric solution of the continuous time reactive congestion control for *N* = 100, T_{on} = 1 ms, and the parameters given in Table C.1

C.1.3.1.2 Discrete T_{off} stability and convergence speed

Figure C.7 shows that a discrete time numeric solution of the reactive congestion control can reproduce the analytic solution when the time step size is small enough. This numeric solution uses 100 steps to converge to a value close to the equilibrium. Assuming a time step size of 100 ms, such an implementation could need around10 seconds to converge to a CL close to the control equilibrium, what is much longer than the time constants to be expected in mobile radio channels and road traffic scenarios.

The numeric solution shown in Figure C.7 is calculated iteratively using equation (C.17) and the parameters given in Table C.1 when setting $\alpha = 0{,}02$:

$$CL(t) = CL(t-\tau_n) + \alpha \times \left(\frac{N \times T_{on}}{CL(t-\tau_n) \times T_a + T_b + T_{on}} - CL(t-\tau_n) \right) \tag{C.17}$$

Equation (C.17) follows from equation (B.11) when using c_{fn} from equation (C.9), setting f_{fn} to one, and using equation (B.4) to calculate CL. α corresponds to the ratio $\frac{\tau_n}{\tau}$. Where τ_n is a fixed time step size used for the numeric solution. α defines how many iteration steps from zero to the time τ of the analytic solution are calculated. Hence, $\alpha = 0{,}02$ used for Figure C.7 corresponds to 50 iteration steps per τ. α is needed to scale the numeric solution in the same way as the analytic solution. It is obvious that the step size of the numeric solution needs to be small to resemble the analytic solution. For a discrete-time congestion control α together with f_{fn} is also essential to fulfil the stability criterium given in equation (B.22).

For a control algorithm it is not essential to resemble the analytic solution of the control function, it should be stable and converge quickly to the equilibrium. Therefore, in ETSI TS 102 687 [i.14] a state machine approach was proposed that discretises the *CL* and the T_{off} time into fife value pairs as shown in Figure C.1 and Figure C.2. To limit the T_{off} step size for each time step, the state machine will only transit from one state to the consecutive one. It is not allowed to step over a state, even when the measured *CL* is not in the range defined for the consecutive state. To determine the direction of the state transition, the *CL* range of the current state is compared with the measured *CL*. If the measured *CL* is within the *CL* range of the current state, then the state and the T_{off} time are not changed. Otherwise, depending on whether the measured *CL* exceeds or is below the *CL* range of the current state, the state transits to the next or the previous state with a longer or shorter T_{off} time.

Figure C.8 shows as solid-coloured lines the *CL* that results from the T_{off} values given in Table A.1 of ETSI TS 102 687 [i.14] for T_{on} = 1 ms. These are straight lines, what follows from equation (C.2). Each line corresponds to one of the states (① to ⑤) of the state machine. The dashed horizontal lines are the *CL* limits for a state transition that correspond to the state with the same colour. The red circles show where in the diagram the table entries for T_{on} = 1 ms are located. For comparison, the control equilibrium $\widetilde{CL}$ for continuous *CL* values according to equation (C.7) with T_a and T_b from Table C.1 is shown as black line.

NOTE: For other values of T_{on} the number of nodes where the state transition limit is reached would be different, as follows from equation (C.2).

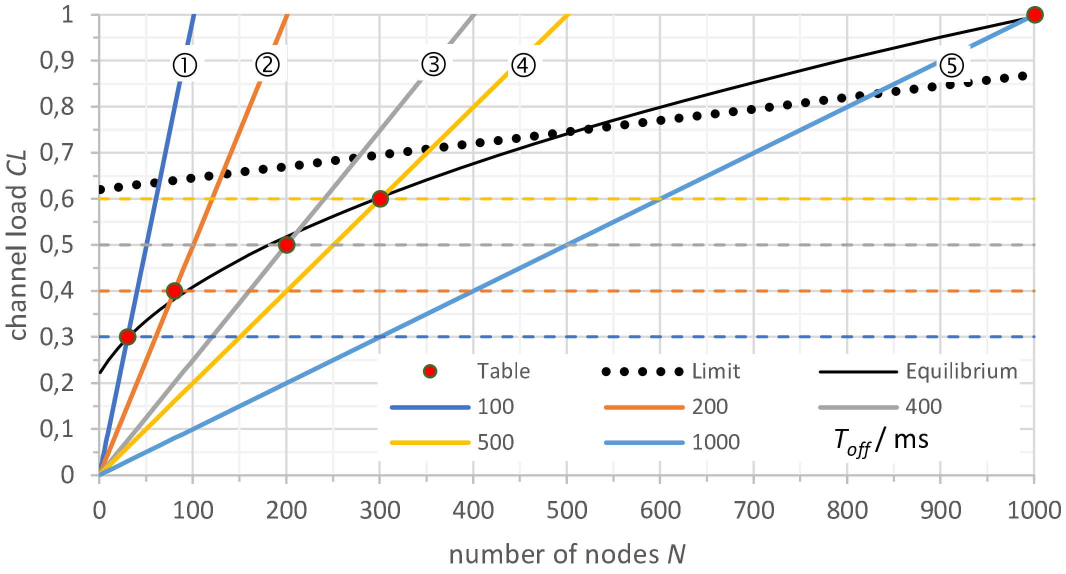


Figure C.8: *CL* resulting for the T_{off} values taken from the reactive DCC Table A.1 in ETSI TS 102 687 [i.14] for T_{on} = 1 ms

Figure C.9 takes a closer look on the control equilibrium of the table based DCC proposed in ETSI TS 102 687 [i.14]. The equilibrium is shown as bold black line. It can only be reached as average over time when the nodes are not synchronized and when only state transitions to the consecutive states are allowed.

The shaded areas (blue, orange, grey) are regions where not all nodes are in the same state so that in average the *CL* results to the respective state transition limit. Hence, in such a region the ratio between the number of nodes in one state and the number of nodes in another state depends on the total number of nodes *N*.

EXAMPLE: For node numbers below the blue shaded area in Figure C.9 all nodes will be in state ①. For a number of nodes within the blue shaded area the limit of *CL* = 0,3 would be exceeded when all nodes are in state ①. Since the nodes are assumed to be not synchronized, they measure the *CL* at random times within a 100 ms interval. Assuming that equilibrium is reached, all nodes measuring a *CL* of more or equal 0,3 will apply state ② all others will apply state ①. Since the nodes are not synchronized and are measuring the *CL* not at the same time, they will do the measurements one after the other with a random time difference. This allows them to get different measurements results and hence to transit to different states, so that in average in this example within the blue shaded area the *CL* will converge to the black line shown in Figure C.9. Annex D shows how the *CL* measurement influences this convergence equilibrium and the convergence speed.

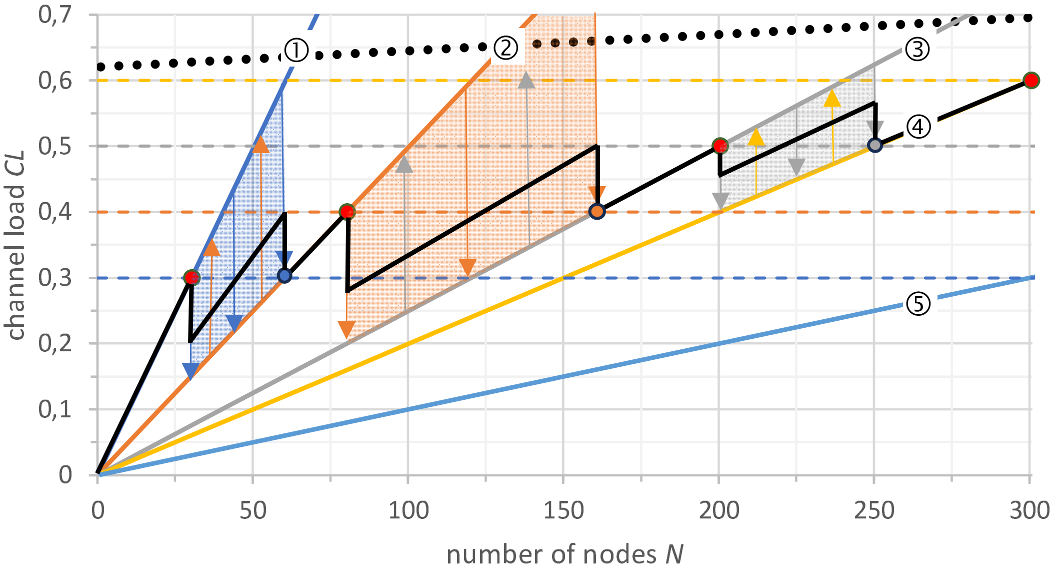


Figure C.9: *CL* resulting from the T_{off} values taken from the reactive DCC Table A.1 in ETSI TS 102 687 [i.14] for T_{on} = 1 ms and the bounded stability regions up to *N* = 300

From Figure C.9 it also gets clear why the nodes should not be synchronized and only transitions between consecutive states are allowed. For the orange shaded area in Figure C.9 it can be seen that when all nodes are synchronized and in state ③ the *CL* will be below the limit of 0,4 and all nodes would synchronously transit to state ②. As a result, the *CL* will jump to a much higher value in the next measurement period, and all nodes will transit back to state ③. This results in a strong *CL* oscillation that can even overload the channel. For the same scenario it can be seen that when all nodes are synchronized and in state ③ the *CL* can be below 0,3. When it would be allowed to transit directly to state ① the channel would be heavily overloaded, and the controller gets immediately instable. For not synchronized nodes this issue is not so obvious, but it still exists and can lead to serious oscillations and channel overload.

C.1.3.2 Stability of the reactive congestion control with filtering according to C2C-CC

In C2C-CC: "Vehicle C-ITS station profile #2037", RS_BSP_240 [i.34] a sliding average filter for the controller input signal is specified. This makes an analysis of the nonlinear control algorithm more complicated. Therefore, such an input filtering is not foreseen in clause B.1.3.

To model this input filtering, the channel load at $t - 2 \times \tau$ is needed. With equation C.8 this results in the dynamic channel load equation (C.18):

$$CL(t) = \frac{N \times T_{on}}{\left(CL(t-\tau) + CL(t-2\times\tau)\right) \times \frac{T_a}{2} + T_b + T_{on}} \tag{C.18}$$

This input filtering does not change the equilibrium channel load. Because it uses the average of two previous channel loads as input, and since in the steady state case all channel loads are considered to be equal to the equilibrium channel load, the average will also be the equilibrium channel load as given in equation (C.7).

Furthermore, when τ is close to zero, the average $\frac{CL(t-\tau)+CL(t-2\times\tau)}{2}$ will be $CL\left(t-\frac{3}{2}\times\tau\right)$:

$$\lim_{\tau\to 0}\frac{CL(t-\tau)+CL(t-2\times\tau)}{2} = CL\left(t-\frac{3}{2}\times\tau\right) \tag{C.19}$$

From equation (C.19) follows that differential equation (C.13), its solution in equation (C.15), and all conclusions drawn for the continuous time behaviour of the reactive approach according to ETSI TS 102 687 [i.14] also apply for the DCC as specified in C2C-CC: "Vehicle C-ITS station profile #2037", RS_BSP_240 [i.34] with a time scaling factor of two. The difference lies in the behaviour of the discrete time / discrete T_{off} implementation of the channel load measurement that is further detailed in Annex D.

C.2 Adaptive congestion control

C.2.1 Control equilibrium of the adaptive congestion control

The adaptive congestion control concept is based on the idea that the radio channel can support a given maximum total target message rate r_g. A Proportional Integral (PI) message rate control algorithm is used to adjust the transmission rate r_j of each network node according to equation (C.20):

$$r_j(t) = (1-\propto)\times r_j(t-\mathrm{\tau}) + \beta_o \times \left(r_g - r(t-\mathrm{\tau})\right) \tag{C.20}$$

$r(t-\tau)$ is the total rate contribution of all nodes N in the previous time step and results from equation (C.21). The time step duration is given by τ:

$$r(t-\tau) = N\times r_j(t-\tau) \tag{C.21}$$

The target message rate r_g that can be supported by the radio channel depends on the message duration, therefore this concept works only fine when the message duration is (almost) fixed and known. Otherwise, a maximum message duration $T_{on\ max}$ needs to be estimated or considered. r_g can then be set according to equation (C.22) so that the channel load is limited to e.g. CL_{max} = 70 %, which is a good default value:

$$r_g = \frac{CL_{max}}{T_{on\ max}} \tag{C.22}$$

Due to the shortcoming that r_g depends on T_{on}, equation (C.20) was reformulated in ETSI TS 102 687 [i.14] so that the estimated constant reciprocal message duration was put into the factor β_o and instead of the total rate contribution r the channel busy ratio CBR which is the measured channel load, was used. This results in equation (C.23):

$$r_j(t) = (1-\propto)\times r_j(t-\mathrm{\tau}) + \beta\times\left(CBR_{target} - CBR(t-\mathrm{\tau})\right) \tag{C.23}$$

This notation has the advantage that it directly uses the measured CBR and that the channel load is limited to CBR_{target} independent of T_{on}. Since the message rate is controlled, the channel utilization of each node still depends on T_{on}:

$$u = r_j \times T_{on} \tag{C.24}$$

Consequently, from equation (C.24) follows in equation (C.25) with equation (B.4) the channel load:

$$CL_a = r_j \times N \times T_{on} \tag{C.25}$$

Assuming that the CL is equal to the measured CBR and $\widetilde{r}_j = r_j(t) = r_j(t-\tau)$ the equilibrium rate $\widetilde{r}_j$ can be calculated from equation (C.26):

$$\widetilde{r}_{\mathrm{j}} = (1-\propto)\times\widetilde{r}_{\mathrm{j}} + \beta\times\left(CBR_{target} - \widetilde{r}_{\mathrm{j}}\times N\times T_{on}\right) \tag{C.26}$$

$$\widetilde{r}_{\mathrm{j}} = \frac{\beta\times CBR_{target}}{\alpha+\beta\times N\times T_{on}} \tag{C.27}$$

With equation (C.25) the channel load equilibrium as function of the number of nodes *N* follows from equation (C.27):

$$\widetilde{CL}_a = \frac{\beta\times N\times T_{on}}{\alpha+\beta\times N\times T_{on}}\times CBR_{target} \tag{C.28}$$

The target channel load CBR_{target} is reached asymptotically for an infinite number of nodes *N* as follows from equation (C.28).

As an example, Figure C.10 shows $\widetilde{CL}_a$ as function of the node number *N* and the T_{on} time as coloured solid lines for the parameter values given in Table 3 of ETSI TS 102 687 [i.14]. $\widetilde{CL}_a$ does not exceed the CBR DCC limit specified in ETSI EN 303 797 [i.32] (dot ted line), but for a small number of nodes and short T_{on} times the channel is underutilized.

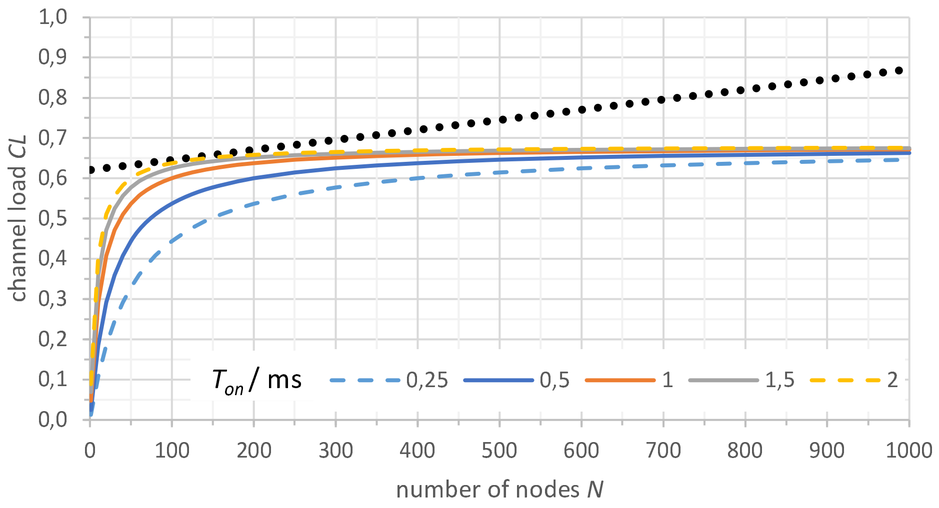


Figure C.10: Equilibrium channel load of adaptive congestion control for the parameter values given in Table 3 of ETSI TS 102 687 [i.14]

C.2.2 Convergence of the adaptive congestion control

C.2.2.1 Continuous time behaviour of the adaptive congestion control

From equation (C.25) the packet rate as function of the channel load CL_a, the number of nodes N, and the packet duration T_{on} can be derived:

$$r_j = \frac{CL_a}{N\times T_{on}} \tag{C.29}$$

Substituting equation (C.29) into equation (C.23) leads to equation (C.30):

$$\frac{CL_a(t)}{N\times T_{on}(t)} = (1-\propto)\times\frac{CL_a(t-\tau)}{N\times T_{on}(t-\tau)} + \beta\times\left(CBR_{target} - CL_a(t-\tau)\right) \tag{C.30}$$

For the assumption that the packet duration is time invariant and equal for all nodes $T_{on}(t) = T_{on}(t-\tau) = T_{on}$ equation (C.30) can be rewritten to:

$$\frac{CL_a(t)-CL_a(t-\tau)}{\tau} = \frac{1}{\tau}\times\left(N\times T_{on}\times\beta\times CBR_{target} - CL_a(t-\tau)\times(\propto + N\times T_{on}\times\beta)\right). \tag{C.31}$$

Equation (C.31) can be written as differential equation for small τ when $\tau\rightarrow 0$:

$$\frac{dCL_a}{dt} = \frac{1}{\tau}\times\left(N\times T_{on}\times\beta\times CBR_{target} - CL_a\times(\propto + N\times T_{on}\times\beta)\right) \tag{C.32}$$

When substituting $A = N\times T_{on}\times\beta\times CBR_{target}$ and $B = \propto + N\times T_{on}\times\beta$ into equation (C.32) it can be rewritten after separation of the variables into:

$$\int\frac{dCL_a}{A-B\times CL_a} = \int\frac{dt}{\tau} \tag{C.33}$$

When integrating equation (C.33) it results to:

$$\frac{t_0-t}{\tau}=\frac{1}{B}log(|A-B\times CL_a|) \tag{C.34}$$

When undoing the substitution for *A* and *B* in equation (C.34) the continuous time solution for the adaptive congestion control results to:

$$\frac{t_0-t}{\tau}=\frac{1}{\propto+N\times T_{on}\times\beta}\times log\left(\left|N\times T_{on}\times\beta\times CBR_{target}-(\propto+N\times T_{on}\times\beta)\times CL_a\right|\right) \tag{C.35}$$

Figure C.11 shows the analytic result calculated with equation (C.35) in red colour and a numeric result as blue crosses for the for N = 100, T_{on} = 1 ms, and the parameters given in in Table 3 of ETSI TS 102 687 [i.14]. The numeric result is obtained with a step size of t/τ= 1 as specified in of ETSI TS 102 687 [i.14]. In this example, for τ= 100 ms the channel load is close to the equilibrium after around 2 seconds, and in practice reaches it after 4 seconds. The convergence time of the discrete time adaptive congestion control is strongly depending on the term $\propto+N\times T_{on}\times\beta$ as will be shown in clause C.2.2.2.

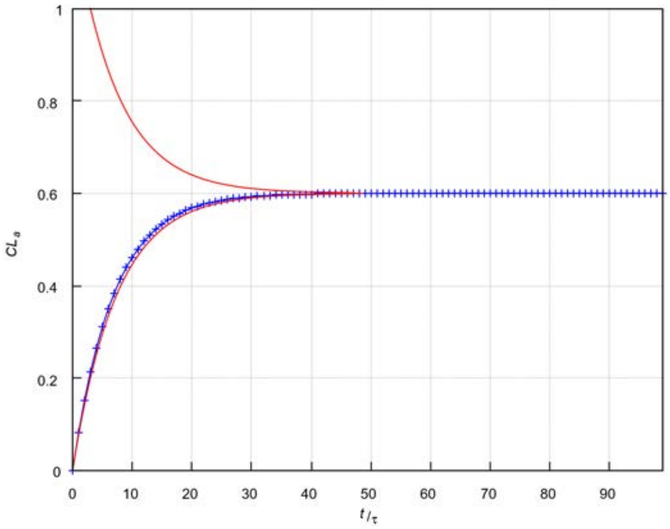


Figure C.11: Analytic and numeric solution of the continuous time adaptive congestion control for *N* = 100, *T_{on}* = 1 ms, and the parameters given in in Table 3 of ETSI TS 102 687 [i.14]

There are two analytic solutions for the continuous time behaviour of the adaptive congestion control depending on whether the initial channel load $CL_a(t_0)$ is above or below the equilibrium channel load $\widetilde{CL}_a$.

When $CL_a(t_0)>\widetilde{CL}_a$ then t_0^+ results from equation (C.36):

$$t_0^+=\frac{\tau}{\mathrm{B}}\times log(CL_a(t_0)\times B-A) \tag{C.36}$$

$$t_0^+=\frac{\tau}{\propto+N\times T_{on}\times\beta}\times log\left(CL_a(t_0)\times(\propto+N\times T_{on}\times\beta)-N\times T_{on}\times\beta\times CBR_{target}\right) \tag{C.37}$$

With t_0^+ from equation (C.37) $CL_a(t)$ results for $CL_a(t_0)>\widetilde{CL}_a$ from equation (C.38):

$$CL_a(t)=\frac{A+e^{B\times\frac{t_0^+-t}{\tau}}}{\mathrm{B}}=\frac{N\times T_{on}\times\beta\times CBR_{target}+e^{\frac{t_0^+-t}{\tau}\times(\propto+N\times T_{on}\times\beta)}}{\propto+N\times T_{on}\times\beta} \tag{C.38}$$

When $CL_a(t_0)<\widetilde{CL}_a$ then t_0^- results from equation (C.39):

$$t_0^-=\frac{\tau}{\mathrm{B}}\times log(A-CL_a(t_0)\times B) \tag{C.39}$$

$$t_0^-=\frac{\tau}{\propto+N\times T_{on}\times\beta}\times log\left(N\times T_{on}\times\beta\times CBR_{target}-CL_a(t_0)\times(\propto+N\times T_{on}\times\beta)\right) \tag{C.40}$$

With t_0^- from equation (C.40) $CL_a(t)$ results for $CL_a(t_0) < \widetilde{CL}_a$ from equation (C.41):

$$CL_a(t) = \frac{A - e^{B\times\frac{t_0^- - t}{\tau}}}{\mathrm{B}} = \frac{N\times T_{on}\times\beta\times CBR_{target} - e^{\frac{t_0^- - t}{\tau}\times(\propto + N\times T_{on}\times\beta)}}{\propto + N\times T_{on}\times\beta} \tag{C.41}$$

C.2.2.2 Stability of the discrete time adaptive congestion control

For calculating the stability criterium given in equation (B.22) the control function $\mathrm{c_{fn}}$, the filtering function $\mathrm{f_{fn}}$, and the equilibrium channel utilization $\tilde{u}$ of the adaptive congestion control is needed.

From equation (C.23) and equation (C.24) the control equation of the adaptive congestion control as function of the channel utilization u_a can be calculated:

$$u_{aj}(t) = (1 - \propto) \times u_{aj}(t - \tau) + T_{on} \times \beta \times \left(CBR_{target} - CBR(t - \tau)\right) \tag{C.42}$$

From equation (B.11) and equation (C.42) it follows that the filter function of the adaptive congestion control $\mathrm{f_{fn}}_a$ is constant and equal to one:

$$\mathrm{f_{fn}}_a\left(CL(t - \tau)\right) = 1 \tag{C.43}$$

With equation (C.43) equation (B.11) simplifies to:

$$u_{aj}(t) = \alpha \times \mathrm{c_{fn}}_a\left(CL_a(t - \tau)\right) + (1 - \alpha) \times u_{aj}(t - \tau) \tag{C.44}$$

From equation (C.42) and equation (C.44) the control function for the adaptive congestion control $\mathrm{c_{fn}}_a$ can be calculated:

$$\mathrm{c_{fn}}_a(CL_a) = T_{on} \times \frac{\beta}{\alpha} \times \left(CBR_{target} - CL_a\right) \tag{C.45}$$

Substituting equation (B.4), equation (C.28), equation (C.43), and equation (C.45) in equation (B.22) leads to equation (C.46):

$$\left|\alpha \times 1 \times \left(T_{on} \times \frac{\beta}{\alpha} \times \left(CBR_{target} - N \times u(t)\right) - u(t)\right)\right| < 2 \times \left|\frac{T_{on}\times\beta\times CBR_{target}}{\alpha+\beta\times N\times T_{on}} - u(t)\right| \tag{C.46}$$

When factorizing equation (C.46) to equation (C.47) it can be simplified to equation (C.48) which is in line with the result given in [i.33] that was found via a series expansion approach:

$$\begin{aligned}(\alpha + \beta \times N \times T_{on}) \times \left|\left(T_{on} \times \beta \times CBR_{target} - T_{on} \times \beta \times N \times u(t) - \alpha \times u(t)\right)\right| &< \\ < 2 \times \left|T_{on} \times \beta \times CBR_{target} - T_{on} \times \beta \times N \times u(t) - \alpha \times u(t)\right|&\end{aligned} \tag{C.47}$$

$$\propto + T_{on} \times N \times \beta < 2 \tag{C.48}$$

This result means that the discrete time adaptive algorithm converges to the $\widetilde{CL}_a$ value from equation (C.28) when the stability criterion of equation (C.48) is fulfilled.

The fastest convergence of the discrete time control is reached for $\propto + T_{on} \times N \times \beta = 1$ where the equilibrium is reached within one time step. For $\propto + T_{on} \times N \times \beta > 1$ the channel load overshoots the equilibrium and converges with an exponentially decaying oscillation. When $\propto + T_{on} \times N \times \beta \ll 1$ the discrete time control converges approximately like the analytic continuous time solution given by equation (C.35).

For the parameter values given in Table 3 of ETSI TS 102 687 [i.14] the stability criterion is given by $T_{on} \times N < 1\ 653{,}3\ ms$.

Since this criterion cannot be guaranteed for large node numbers and long packet durations, the algorithm was enhanced in ETSI TS 102 687 [i.14] by a control loop gain saturation that limits the factor of T_{on} in the second term of equation (C.26) to a constant value G_{max} and by an input filtering function. While the filtering function has no influence on the control equilibrium function, a saturation of the control loop gain by setting the second term of equation (C.26) to a constant G_{max} slightly reduces the channel utilization and has an influence on the convergence speed (see clause C.2.2.3). In ETSI TS 102 687 [i.14] different values for G_{max} are defined when CBR_{target} is larger or smaller than $CL_a(t-\tau)$. For the control equilibrium only G^{+}_{max} is relevant since the resulting new channel load equilibrium is below CBR_{target} and the gain saturation is realized by replacing the second term of the control equation (C.26) by G^{+}_{max}. From this follows the control equilibrium $\widetilde{r_{sj}}$ in equation (C.49) for the gain saturated case:

$$\widetilde{r_{\text{sj}}} = (1-\propto) \times \widetilde{r_{\text{sj}}} + G^{+}_{max} \qquad \text{(C.49)}$$

What results to a fixed equilibrium packet rate $\widetilde{r_{sj}}$ independent of the channel utilization:

$$\widetilde{r_{sj}} = \frac{G^{+}_{max}}{\propto}. \qquad \text{(C.50)}$$

From equation (C.50) follows with equation (C.25) a linear relation between $N \times T_{on}$ and the equilibrium channel load $\widetilde{CL_{as}}$ as shown by equation (C.51) for cannel loads CL_a within the lower gain saturation area (see Figure C.12):

$$\widetilde{CL_{as}} = \frac{G^{+}_{max}}{\propto} \times N \times T_{on} \qquad \text{(C.51)}$$

The gain saturation areas result from the gain saturation values G^{+}_{max} and G^{-}_{max} that are replacing the second term of equation (C.26). Based on this the gain saturation areas are given by an upper area with a lower bound CL^{-}_{a} as shown in equation (C.52) and a lower area with an upper bound CL^{+}_{a} as shown in equation (C.53):

$$CL^{-}_{a} = CBR_{target} - \frac{G^{-}_{max}}{\beta} \qquad \text{(C.52)}$$

$$CL^{+}_{a} = CBR_{target} - \frac{G^{+}_{max}}{\beta} \qquad \text{(C.53)}$$

Figure C.12 shows these areas and the impact of the gain saturation on the equilibrium channel load for the parameter values given in Table 3 of ETSI TS 102 687 [i.14]. It can be seen that in the gain saturation area below CL^{+}_{a} the equilibrium channel load follows the linear relation given by equation (C.51), while above CL^{+}_{a} it follows the non-linear equation (C.28). The upper gain saturation area is only reached in dynamic channel load scenarios. It has no influence on the equilibrium channel load.

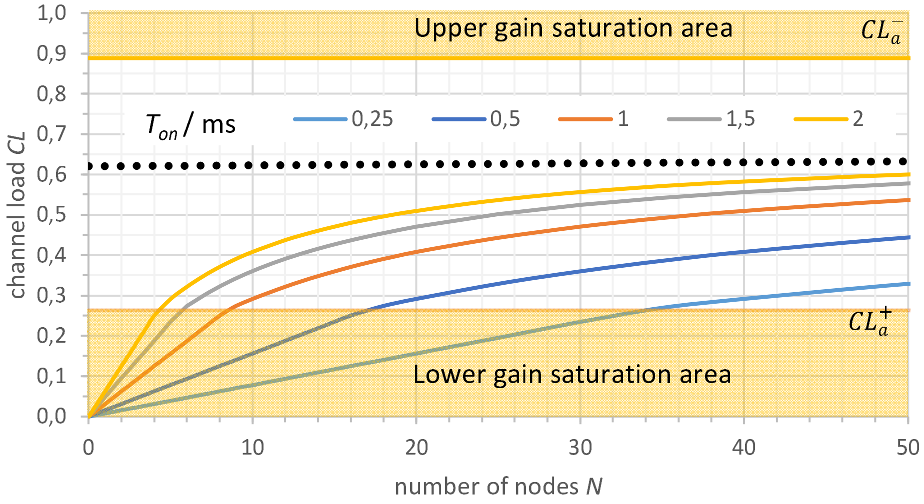


Figure C.12: Detail of equilibrium channel load of adaptive congestion control for the parameter values given in Table 3 of ETSI TS 102 687 [i.14] showing the effect of the gain saturation

The filtering as proposed in ETSI TS 102 687 [i.14] increases the stability range for $T_{on} \times N$ by a factor of two. Hence, the control loop can converge to an equilibrium for twice as many nodes or for doubled message sizes. Details about this need to be investigated.

C.2.2.3 Convergence speed of the discrete time adaptive congestion control

In [i.33] a series expansion approach was used to find the channel load values after each time step of the discrete time adaptive congestion control. From there, with $A = N \times T_{on} \times \beta \times CBR_{target}$ and $B = \propto + N \times T_{on} \times \beta$ the channel load CL_a after n time steps can be calculated according to equation (C.54) for the discrete time adaptive congestion control under the assumption that all nodes are synchronized. The more realistic case for unsynchronized nodes is discussed in Annex D:

$$CL_a(n \times \tau) = \frac{(1-B)^n \times (CL_a(0) \times B - A) + A}{B} \qquad \text{(C.54)}$$

From equation (C.54) the convergence speed of the discrete time adaptive congestion control can be calculated. Where the convergence speed is defined by the time where the channel load crosses the boundaries of ±5 % deviation from the equilibrium value and afterwards stays within these boundaries when applying a channel load step from 0 % to 100 % or from 100 % to 0 %. Since the convergence times depend on the initial conditions at the time t = 0 s (see Figure C.11) these conditions of the network nodes need to be defined. An initial transmission rate $r_j = 0$ and a resulting $CL_a(0) = 0$ can be used to test an implementation of the control algorithm, while the example with $CL_a(0) = 1$ is more to demonstrate what happens when the channel is fully loaded and $r_j = \frac{1}{N \times T_{on}}$, what is a bit of an arbitrary assumption just to show the difference to $r_j = 0$.

For $1 - B > 0$ the power function $(1 - B)^n$ is monotonically increasing (see examples in Figure C.13), for $1 - B < 0$ it oscillates between positive results for even time steps values n and negative results for odd values of n. Since the factor $CL_a(0) \times B - A$ is negative for $CL_a(0) = 0$ this leads to an overshoot of the equilibrium $\frac{A}{B}$ (equation (C.28)) as can be seen as an example in Figure C.14.

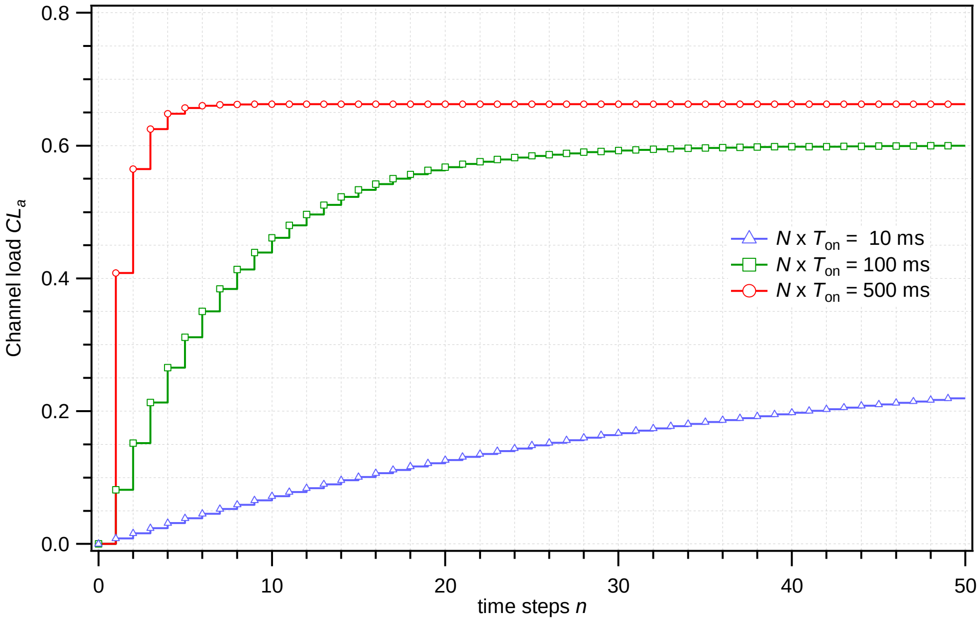


Figure C.13: Channel load of adaptive congestion control for different values of N x T_{on} resulting from equation (C.54) for the parameter values given in Table 3 of ETSI TS 102 687 [i.14]

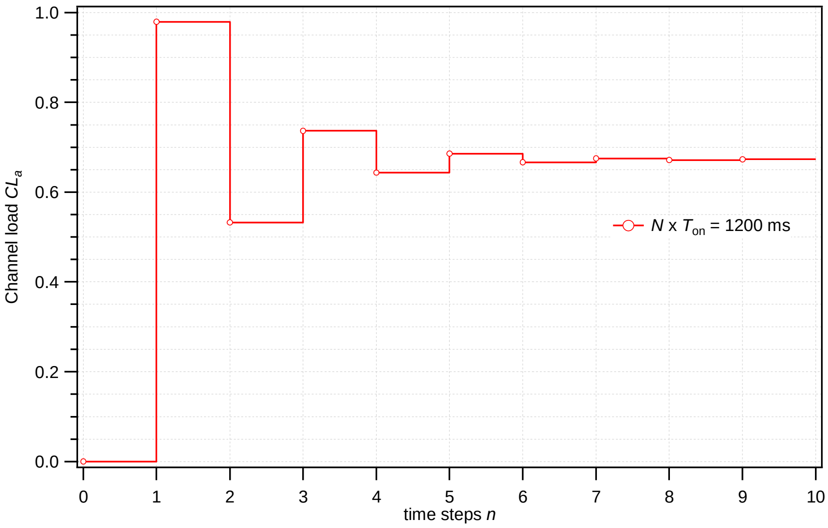


Figure C.14: Channel load of adaptive congestion control for N x T_{on} = 1 200 ms resulting from equation (C.54) for the parameter values given in Table 3 of ETSI TS 102 687 [i.14]

Thus, for $B < 1$ the number of steps n_c to reach convergence results from equation (C.54) when setting CL_a to 95 % or 105 % of the equilibrium $\frac{A}{B}$ (equation (C.28)). Which value to take depends on the initial channel load $CL_a(0)$ as shown in equation (C.55) and equation (C.56):

$$\text{For } B < 1 \text{ and } CL_a(0) = 0 \text{ follows } \frac{A}{B} \times 0{,}95 = \frac{(1-B)^{n_c^-} \times (-A) + A}{B} \qquad \text{(C.55)}$$

$$\text{For } B < 1 \text{ and } CL_a(0) = 1 \text{ follows } \frac{A}{B} \times 1{,}05 = \frac{(1-B)^{n_c^+} \times (B-A) + A}{B} \qquad \text{(C.56)}$$

The time steps n_c^- to reach 95 % of the channel load equilibrium for an initial channel load of 0 result from equation (C.57). For an initial message rate $r_j = \frac{1}{N \times T_{on}}$ the time steps n_c^+ to reach 105 % of the channel load equilibrium result from equation (C.58). Figure C.15 compares the results for n_c^- and n_c^+ from equation (C.57) and equation (C.58) for the initial cannel load $CL_a(0)$ equal to 0 or respectively equal to 1:

$$\text{For } B < 1 \text{ and } CL_a(0) = 0 \text{ follows } n_c^- = \frac{ln(0{,}05)}{ln(1-\mathrm{B})} = \frac{ln(0{,}05)}{ln(1-\propto-N \times T_{on} \times \beta)} \qquad \text{(C.57)}$$

$$\text{For } B < 1 \text{ and } CL_a(0) = 1 \text{ follows } n_c^+ = \frac{ln\left(\frac{A \times 0{,}05}{B-A}\right)}{ln(1-\mathrm{B})} = \frac{ln\left(\frac{N \times T_{on} \times \beta \times CBR_{target} \times 0{,}05}{\propto + N \times T_{on} \times \beta \times \left(1 - CBR_{target}\right)}\right)}{ln(1-\propto-N \times T_{on} \times \beta)} \qquad \text{(C.58)}$$

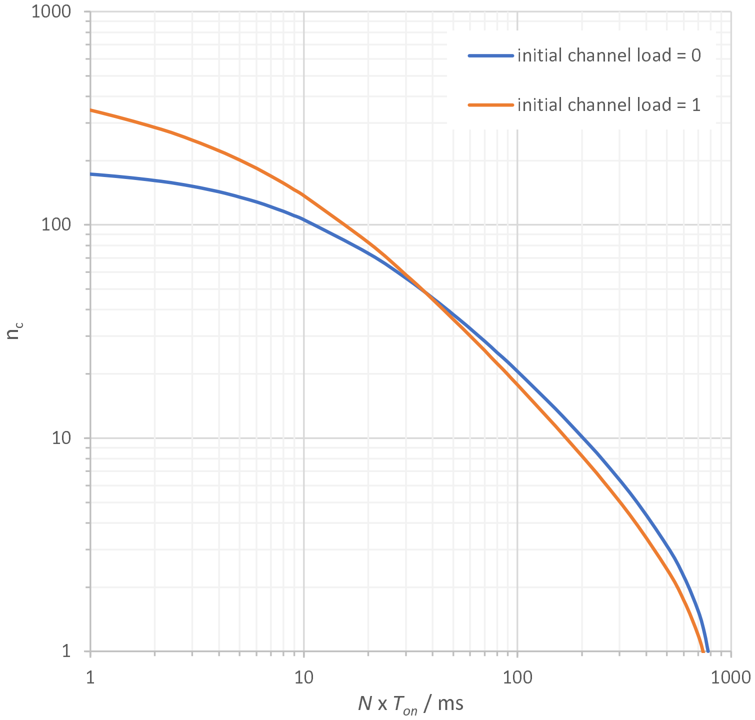


Figure C.15: Number of time steps to reach ±5 % deviation from the equilibrium channel load for the adaptive congestion control with parameter values as given in Table 3 of ETSI TS 102 687 [i.14]

For $B > 1$ the channel load will overshoot the equilibrium as has been shown in Figure C.14. This overshoot can overload the channel, and the convergence time consists of the channel overload recovery time plus the exponential channel load decay time. The linear channel load model will not hold for the channel load saturation at high loads. But it can give at least a rough estimation of the decay time as long as that CBR_{target} parameter is below a channel load of 0,8. The envelope of the channel load decay is given by equation (C.59):

$$\text{For } B > 1 \text{ follows } CL_{a\ envelope}(n) = \frac{A}{B} - \left(CL_a(0) - \frac{A}{B}\right) \times e^{ln(B-1) \times n} \qquad \text{(C.59)}$$

With a gain saturation G_{max}^{+} the convergence time increases, since below CL_a^{+} the channel load CL_{as} follows equation (C.60) which is less steep in n compared to equation (C.54):

$$\text{For } CL_a < CL_a^{+} \text{ follows } CL_{as}(n \times \tau) = \frac{(1-\alpha)^n \times (CL_a(0) \times \alpha - G_{max}^{+} \times N \times T_{on}) + G_{max}^{+} \times N \times T_{on}}{\alpha} \qquad \text{(C.60)}$$

Depending on whether the channel load equilibrium is below or above CL_a^{+}, the convergence speed can either be determined from equation (C.60) or by piecewise use of equation (C.60) up to CL_a^{+} and from there by use of equation (C.54) as shown in the beginning of the present clause.

ETSI TS 102 687 [i.14] foresees despite the gain saturation that was described already in clause C.2.2.2 a filtering based on the last three channel load measurements. When $N \times T_{on}$ is constant over time this filtering is given by equation (C.61) and has an impact on the convergence behaviour:

$$CL_{af}(t) = (1-\propto) \times CL_{af}(t-\tau) + N \times T_{on} \times \beta \times \left(CBR_{target} - \left(\frac{CL_{af}(t-\tau)}{2} + \frac{CL_{af}(t-2\times\tau) + CL_{af}(t-3\times\tau)}{4}\right)\right) \text{(C.61)}$$

Figure C.16 and Figure C.17 show based on some examples the impact of the gain saturation and the input filtering as specified in ETSI TS 102 687 [i.14] with the parameter values given in Table 3 of ETSI TS 102 687 [i.14].

The given input filtering does not improve the stability it even increases the overshoots for $N \times T_{on} > 826{,}7\ ms$ as shown in Figure C.17 and can even lead to an overshoot for $N \times T_{on} < 826{,}7\ ms$ as shown in Figure C.16. An analytic evaluation of this behaviour is too complex to be shown in the present document.

Detailed evaluation of the gain compression independently from the filtering show that the gain compression effectively reduces the overshoot while only slightly prolonging the convergence time. This evaluation also shows that an output filtering can improve the stability, since it does not add additional delay in the control loop. But such an output filtering also increases the convergence time and therefore the right balance between stability and convergence time needs to be found.

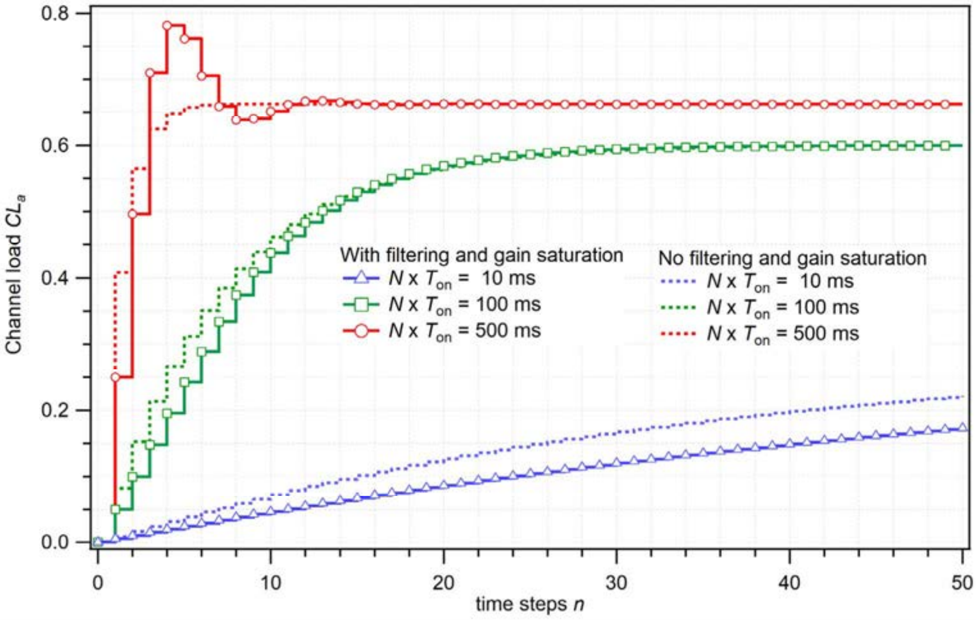


Figure C.16: Comparison of the difference between the channel load given by equation (C.54) for a basic adaptive DCC and the channel load of a DCC including filtering and gain saturation

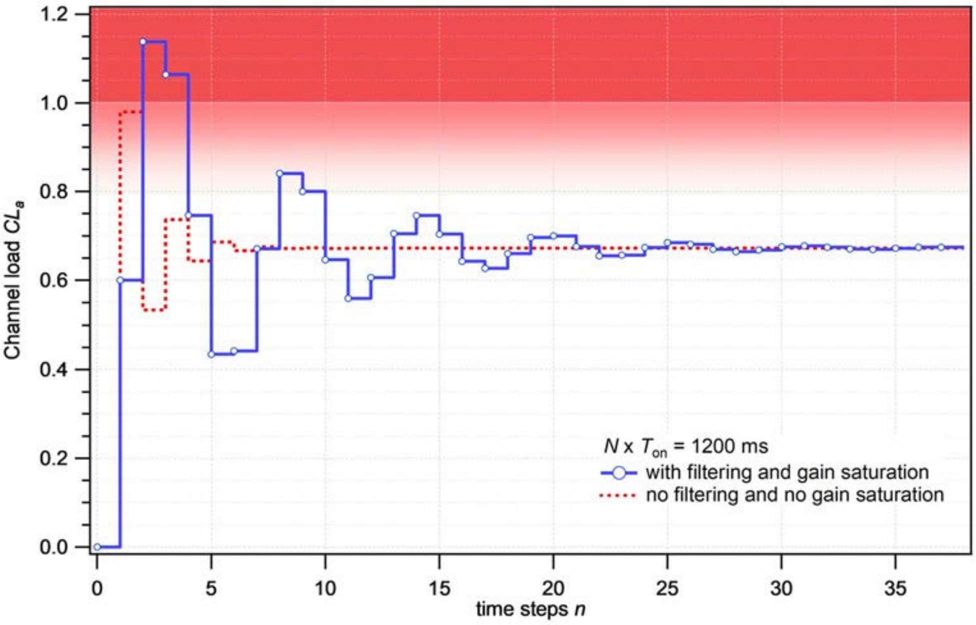


Figure C.17: Comparison of the difference between the channel load given by equation (C.54) for a basic adaptive DCC and the channel load of a DCC including filtering and gain saturation

C.2.2.4 Time behaviour of a discrete time adaptive congestion control implementation

For the evaluation in the previous clauses of Annex C, it was assumed that the channel load can be determined and influenced according to equation (C.2) instantaneously. Both does not hold for a DCC that controls the packet rate. A change of the channel utilization is done by adjusting the time T_{off} in between two transmissions according to the packet duration T_{on} that is given by the MCS and the message size. This means that changing the channel utilization needs at least a time of $T_{on}+T_{off}$ to take effect, what follows from equation (B.6). The same applies to the channel load measurement, the correct channel load can only be determined when the measurement time is long enough to account for all network nodes in range. Annex D will show the impact of the channel load measurement on the control behaviour. In this clause the time scaling of the convergence process is evaluated.

Clause C.2.2.3 only dealt with time steps to simplify the evaluation of the discrete time adaptive congestion control. To get the convergence function over time of a real implementation, the minimum time step duration $\Delta t_j(k)$ for node j and step k can be assumed to be $T_{on\,j}(k) + T_{off\,j}(k)$. The adaptive congestion control algorithm determines the packet rate r_j for the next time step of node j with equation (C.23). The minimum time step duration Δt_j is the reciprocal of this packet rate r_j as shown in equation (C.62):

$$\Delta t_j = \frac{1}{T_{on\,j}+T_{off\,j}} = \frac{1}{r_j} \tag{C.62}$$

The time t_{nj} after n time steps of node j is then the sum of the time step durations Δt_{kj}, where k is the time step index. Δt_{0j} is the initial time step duration resulting from $CL_a(0)$. This value can be infinite when $CL_a(0)=0$ and is therefore not included in the sum:

$$t_{nj} = \sum_{k=1}^{n} \Delta t_{kj} \tag{C.63}$$

When assuming that all nodes j behave similar, equation (C.63)can be rewritten with equation (C.54) and equation (C.25) to equation (C.64). Where A and B are given in clause C.2.2.3.

$$t_n = B \times N \times \sum_{k=1}^{n} \frac{T_{on\,k}}{(1-B)^k \times (CL_a(0) \times B - A) + A} \tag{C.64}$$

Assuming that T_{on} is constant over time and equal for all nodes, then equation (C.64) can be rewritten to equation (C.65) when using the substitution $a = \frac{A}{A-CL_a(0)\times B}$ and $b = 1 - B$.

$$t_n = \frac{B \times N \times T_{on}}{A - CL_a(0) \times B} \times \sum_{k=1}^{n} \frac{1}{a-b^k} \tag{C.65}$$

The sum over $\frac{1}{a-b^k}$ has no simple analytic solution, but it can be converted into an integral that results for $B<1$ in equation (C.66):

$$\int_1^n \frac{1}{a-b^k}\,dk = t_{\text{offs}} + \frac{k_{\text{offs}}+n}{a} - \frac{\ln(a-b^{k_{\text{offs}}+n})}{a\ln(b)} \tag{C.66}$$

The offset coefficient k_{offs} in equation (C.70) can be found after some calculation when subtracting the first two terms of the sum in equation (C.65) from each other (equation (C.67) and equation (C.68)):

$$\frac{1}{a-b} = t_{\text{offs}} + \frac{k_{\text{offs}}+1}{a} - \frac{\ln(a-b^{k_{\text{offs}}+1})}{a\ln(b)} \tag{C.67}$$

$$\frac{1}{a-b^2} + \frac{1}{a-b} = t_{\text{offs}} + \frac{k_{\text{offs}}+2}{a} - \frac{\ln(a-b^{k_{\text{offs}}+2})}{a\ln(b)} \tag{C.68}$$

$$k_{\text{offs}} = \frac{\ln\left(b \times \mathrm{e}^{\frac{a \times \ln(b)}{b^2-a}} - 1\right) - \ln\left(\mathrm{e}^{\frac{a \times \ln(b)}{b^2-a}} - 1\right) - 2 \times \ln(b) + \ln(a)}{\ln(b)} \tag{C.69}$$

The offset coefficient t_{offs} then results from equation (C.67):

$$t_{\text{offs}} = \frac{\ln(b) \times ((a-b) \times k_{\text{offs}} - b) + (b-a) \times \ln(a-b^{k_{\text{offs}}+1})}{(a \times b - a^2) \times \ln(b)} \tag{C.70}$$

With the offset coefficients from equation (C.69) and equation (C.70) the time t_n corresponding to a certain time step number n can be calculated for B<1 according to equation (C.71):

$$t_n = B \times N \times T_{on} \times \left(\frac{t_{\text{offs}}}{A - CL_a(0) \times B} + \frac{k_{\text{offs}} + n}{A} - \frac{\ln\left(\frac{A}{A - CL_a(0) \times B} - (1-B)^{k_{\text{offs}}+n} \right)}{A \times \ln(1-B)} \right) \qquad \text{(C.71)}$$

For B<1 equation (C.54) and equation (C.71) can be used to calculate a continuous time solution of the channel load $Cl_a(t)$ that is to be expected when the network nodes are not synchronized in time. Figure C.18 shows this continuous time solution for the same $N \times T_{on}$ values and the same DCC configuration that were used for the results shown as dashed lines in Figure C.16 for the parameter values from Table 3 of ETSI TS 102 687 [i.14].

Figure C.19 shows for the parameter values given in Table 3 of ETSI TS 102 687 [i.14] the convergence time calculated with equation (C.71) from the number of time steps n_c^- obtained in clause C.2.2.3 (see Figure C.15) to reach 95 % of the channel load equilibrium for an initial channel load of $Cl_a = 0$ and an initial packet rate of $r_j(t_0 = 0) = 0$.

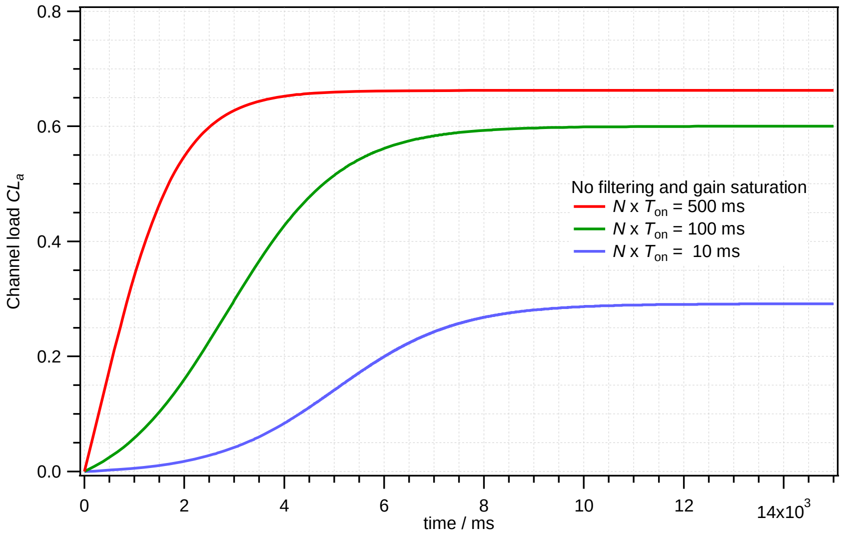


Figure C.18: Channel load as function of time for a basic adaptive rate controller with an initial packet rate of $r_j(t_0 = 0) = 0$

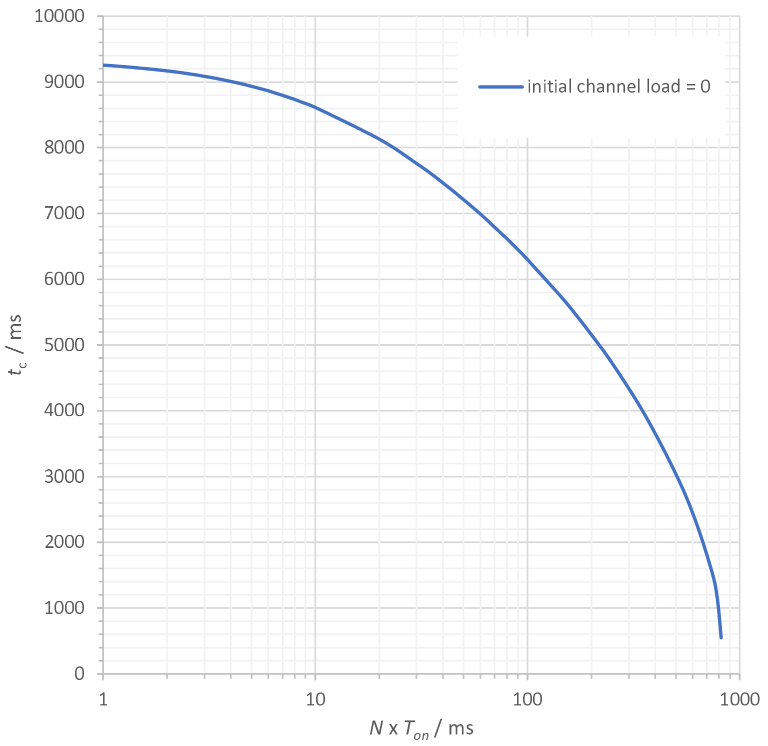


Figure C.19: Time t_c to reach 95 % of the equilibrium channel load when starting from an empty channel for the adaptive congestion control

C.3 Power control

Adapting the output power level to control the channel congestion is used in centrally managed radio networks since the central controller has the knowledge of the power settings of transmitters that are out of radio range of each other.

Because a power control has no direct impact on the local channel load, the local channel load cannot be used without modifications as feedback in a decentralized power control loop. There are two possibilities to use local data as feedback for such a control loop. Either the channel load measurement threshold is modified according to the transmit power level as described in [i.36], or since this is not possible with most of the chipsets, the number of DSRC stations within a transmit power level dependent radius is counted and used together with the channel occupancy time of these transmitters as feedback metric.

Even with a modified local feedback value, the power control cannot control the local channel load independently from the vehicle density to an optimum value, since it estimates the remote vehicle density based on the local one. Hence, the most reasonable use of a power control is to avoid channel overload at distant ITS stations. This implies that the channel load measured by these remote transmitters should be known, since a "power control" based on local channel load information lacks negative feedback necessary to "control" the power level. This is because when reducing the transmit power level, a transmitter gets invisible to other transmitters far away. In turn these transmitters will increase their transmit power level since the channel load at this position decreases. This increase in transmit power level has no impact on the channel load in the vicinity of the transmitting station, but it causes even more channel load at positions far away.

A decentralized power control therefore needs a management channel that has a longer range than the radio channel used for message dissemination. This could be done by multi hop dissemination of the power settings with a robust MCS.

A power control has further difficulties. The vehicle density can vary by more than factor 10, implying that a power range of more than 20 dB is necessary to cope with these variations by keeping always the same number of vehicles within range. Different transmit power levels result in different ranges causing a lot of stations to be hidden, and the CSMA/CA algorithm to fail. Therefore, the packet collision rate statistics with power control will get worse and exhibit a more ALOHA like behaviour. Therefore, a power control should only be used to support a rate control.

Adapting the output power level only based on the local channel load can lead to spatial oscillations. As an example Figure C.20 and Figure C.21 show the simulation result for a low traffic density scenario in two lanes with 35 m vehicle separation after 25 iterations (steady state) of the algorithm specified in SAE J2945/1 [i.39]. For this simulation a channel load measurement threshold of -85 dBm was chosen and a simple free space channel model was used. The packets of 0,8 ms duration were generated with a frequency of 10 Hz to show the behaviour of the power control algorithm only.

The result for this scenario show in Figure C.20 and Figure C.21 oscillations of the transmit power level and the channel load as function of the vehicle position. This spatial oscillation is caused by the missing negative feedback when using the local channel load as feedback value in the control loop. Similar problems have been observed in [i.37] when simulating the ETSI joint power and rate congestion control specified in ETSI TS 102 687 [i.14].

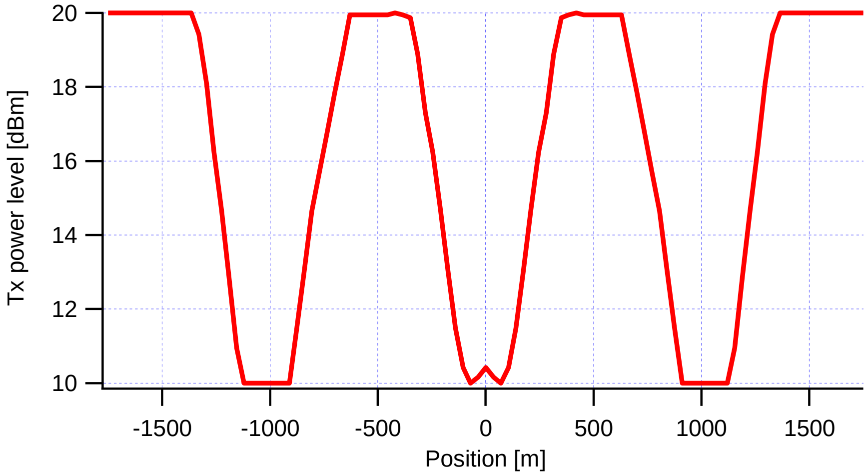


Figure C.20: Power level oscillations in space for light street traffic

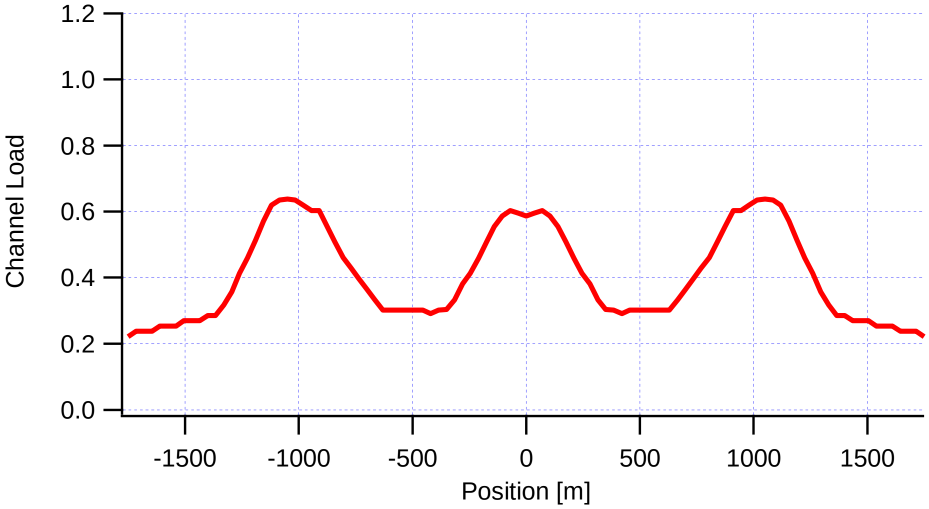


Figure C.21: Channel load oscillations in space for light street traffic

Annex D:
Channel load measurement

D.1 Channel load measurement overview

In Annex C it was assumed that the channel load can be measured in any point of time. In practice it is measured by determining the total channel active time $T_{on\ total}$ and the total channel idle time $T_{off\ total}$ over a certain measurement period and then by calculating the measured channel load CL_m according to equation (D.1). This measured channel load is often called channel busy ratio CBR:

$$CL_m = CBR = \frac{T_{on\ total}}{T_{on\ total} + T_{off\ total}} \tag{D.1}$$

When the measurement period is shorter than the idle time T_{off} between two consecutive messages transmitted by a certain node, the channel utilization of this node will be considered only in some of the channel load measurements. Hence, the measurement result will not be stable even when all nodes are not changing their channel utilization. Furthermore, such a sliding window approach to measure the channel load does exhibit a linear phase over frequency and has no flat frequency response. This has an influence on the control loop stability since some frequencies will be amplified in the control loop, leading to instabilities. Some authors [i.38] even proposed to inject noise into the measurement results to avoid such a feedback effect in the control loop.

In addition, for an ITS-G5 access layer the measurement times are not synchronized what usually improves stability but complicates an analytic approach to determine stability. Even the unsynchronized measurement times will improve stability, they should not be taken for granted, since some implementation might synchronize them with the GPS time. Therefore, the stability determination should be done for the worst case of synchronized nodes to guaranty stability for any random configuration. Such an investigation has been done in Annex C.

In Annex D a simulation with 1 ms time slots and a random start configuration was used, where the channel was first empty and the initial T_{off} value of each node has been determined by the first step of the adaptive algorithm plus a random value between -1 ms and +1 ms. The first transmission time of each node has been determined from the initial channel load resulting from the initial T_{off} value by a random experiment. Starting with the first time slot and the first node a random number between 0 and 1 is drown, if this number is smaller than the initial channel load then the time slot is used for transmission of the actual node and the next node starts the same random experiment at the consecutive time slot, else the random experiment is repeated for the next time slot with the same node. This process runs until all nodes found a random transmission time slot. For the simulation an idealized MAC is used that avoids any packet collisions, hence when a time slot is already in use, the MAC looks for the next free slot and puts the transmission there. This means that each transmission increases the channel load. The amount of this increase is only given by the T_{off} value. In contrast the ITS-G5 MAC allows for simultaneous transmissions resulting in a packet loss by self-interference and roughly no channel load increase by simultaneous transmissions. This causes a channel load saturation effect not investigated in Annex C, therefore the idealized MAC simplification was chosen to allow a comparison of the results from Annex C and Annex D.

D.2 Influence of the channel load measurement on the reactive congestion control

First simulation results of the table based reactive algorithm show chaotic behaviour, even under static traffic and radio channel conditions. Such a chaotic behaviour is typical for nonlinear differential equations as given by the step function resulting from the table entries. Figure D.1 shows such a behaviour for a reactive DCC according to Table A.1 in ETSI TS 102 687 [i.14] for 401 nodes, T_{on} = 1 ms, and 100 ms CBR measurement time. The blue bars at the bottom of Figure D.1 show the transmission events. Even the scale is such that not all channel idle periods can be seen in this figure, it is obvious that the white spaces in between the transmissions are not deterministic. The coloured line shows in blue an underutilization and in red an over utilization of the channel. In average it fluctuates chaotically around the expected 60 % channel load. The Average is calculated by a sliding window of 1 second length. The CBR result obtained with a 100 ms sliding window duration is shown in black, it jumps chaotically between different values in the range from 0 to 100 %. This fluctuating value is the input to the reactive DCC.

To visualize these fluctuations for different number of nodes and thereby different T_{off} values the shaded region in Figure D.2 shows the range of channel load values measured with a sliding window duration of 1 second that were calculated for a time span of 20 seconds after bounded stability was reached. The green line shows the average of these channel load values. When comparing this to Figure C.9 the theory only fits in the far-left part of Figure D.2. This is because the measurement time span of 100 ms is much shorter than the T_{off} time of each node necessary to limit the channel load when there are more than 40 nodes in range.

To reduce the chaotic behaviour of the measured channel load, the measurement period can be increase as specified in The C2C-CC Profile, where it was doubled to 200 ms. Figure D.3 shows the result for this doubled measurement period. As expected, the result is close to theory for around double the number of nodes compared to a measurement period of 100 ms. Still, for more than 80 nodes the behaviour gets again chaotic.

Consequently, the CBR measurement duration should be long enough to account for the transmissions of all nodes to avoid erratic behaviour of the control loop. As outline in the beginning of the present clause and in clause C.2.2.4, the easiest and most effective way of doing this is to make the measurement duration equal to $T_{on} + T_{off}$. Since in practice all nodes use different values of T_{on} and T_{off} this will automatically desynchronize the measurement times, and even when all T_{on} times are equal, each node will measure a (slightly) different CBR, resulting in (slightly) different T_{off} time for each node. Figure D.4 shows that this leads for the reactive DCC for up to 300 nodes to theoretical result shown in Figure C.9. For more nodes the MAC of ITS-G5 starts to avoid simultaneous transmissions what makes the channel access less predictive and the channel load more erratic.

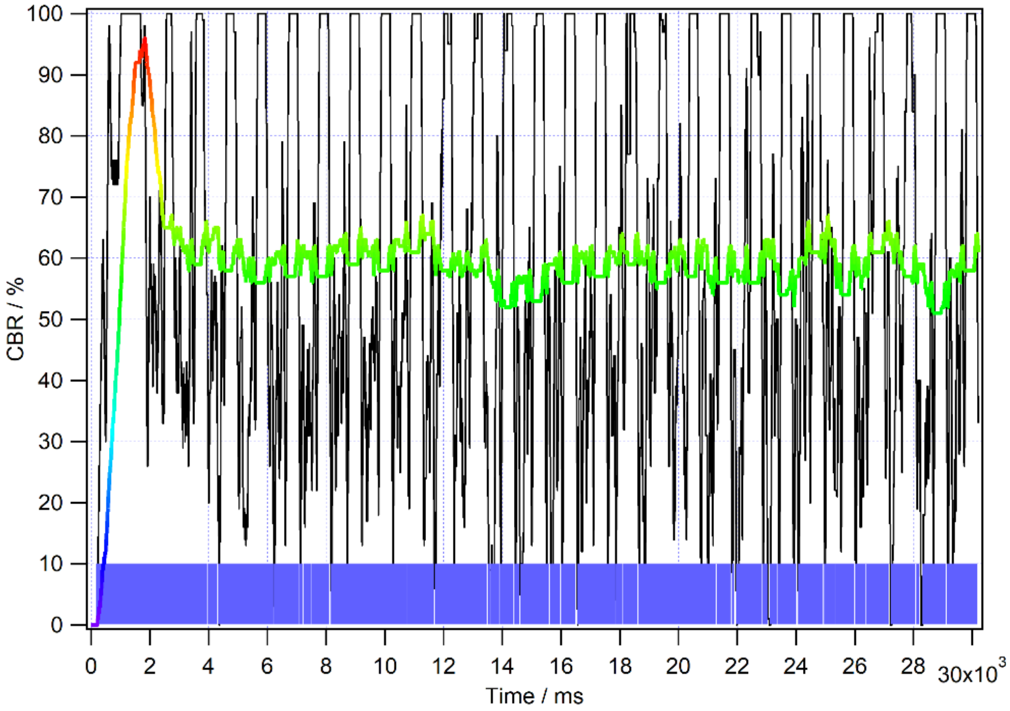


Figure D.1: Time behaviour for a reactive DCC according to Table A.1 in ETSI TS 102 687 [i.14] for 401 nodes, T_{on} = 1 ms, and 100 ms CBR measurement time

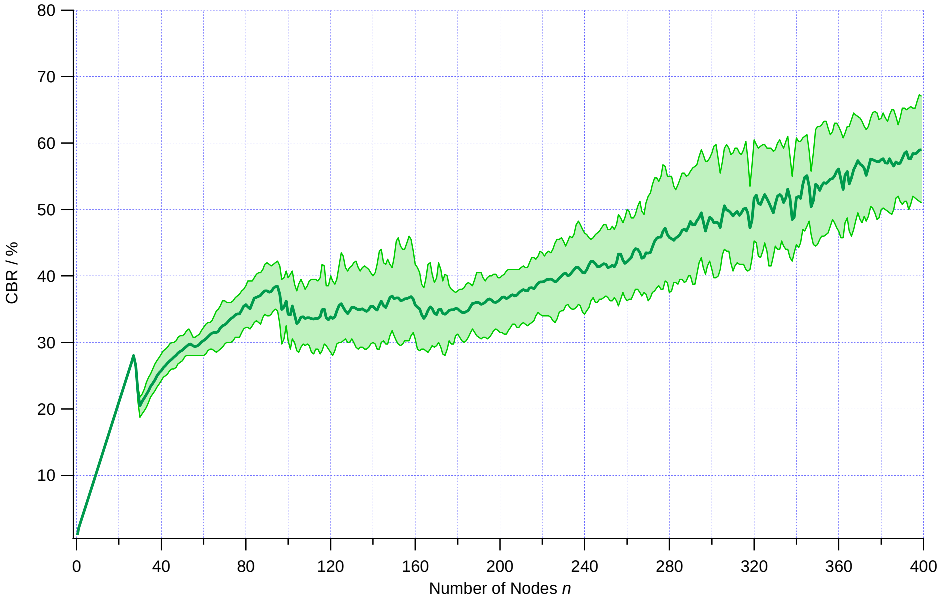


Figure D.2: Bounded stability for a reactive DCC according to Table A.1 in ETSI TS 102 687 [i.14] for T_{on} = 1 ms and 100 ms CBR measurement time

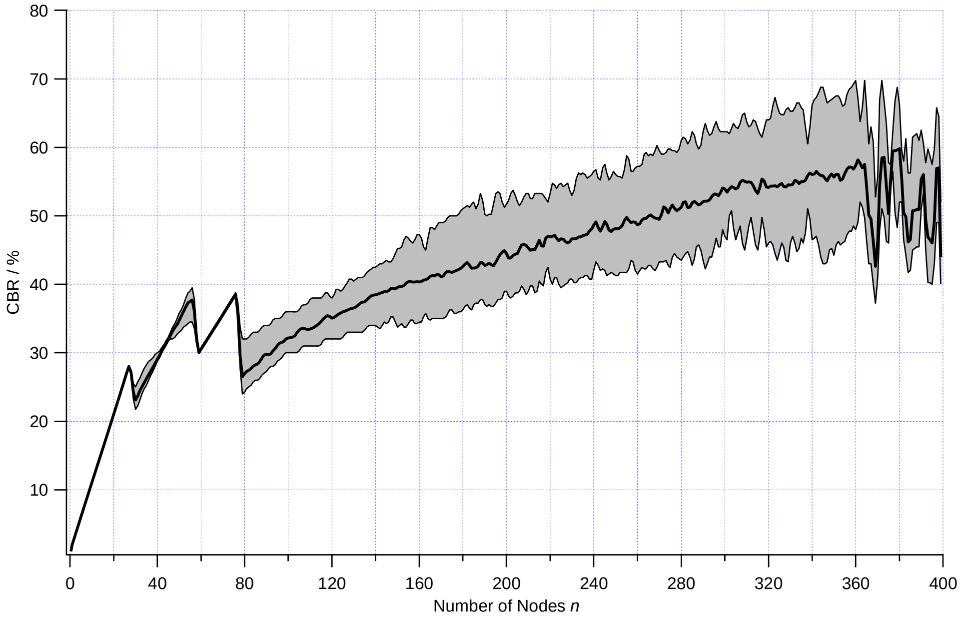


Figure D.3: Bounded stability for a reactive DCC according to C2C-CC [i.34] for T_{on} = 1 ms and 200 ms CBR measurement time

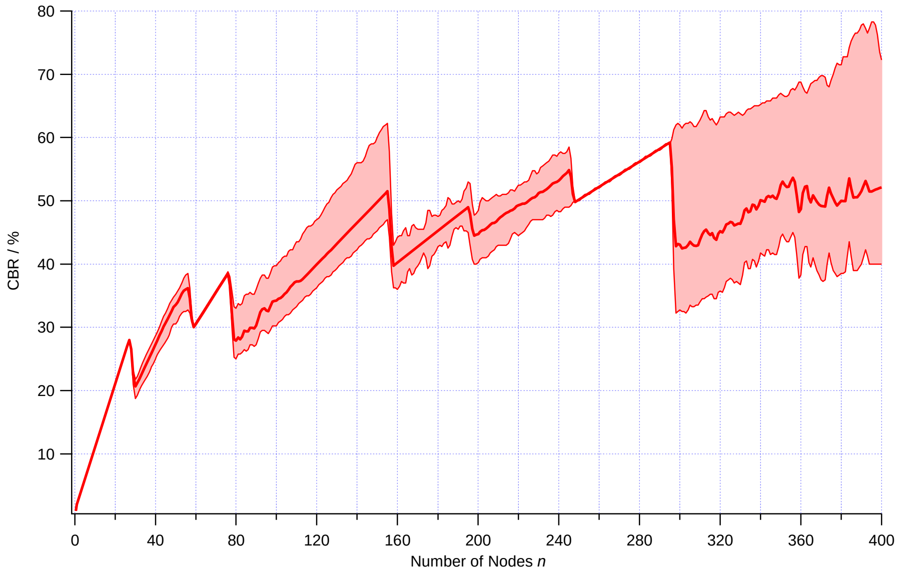


Figure D.4: Bounded stability for a reactive DCC according to C2C-CC [i.34] for T_{on} = 1 ms and a CBR measurement time equal to $T_{on}+T_{off}$

D.3 Influence of the channel load measurement on the adaptive congestion control

D.3.1 CBR measurement with a fixed 100 ms measurement time interval

When using a plain adaptive congestion control with a fixed CBR measurement time of 100 ms without gain saturation and without a T_{off} limitation the CBR averaged over 1 second stays after 30 seconds bounded within a 10 % margin for up to around 500 network nodes and a T_{on} of 1 ms as can be seen in Figure D.5.

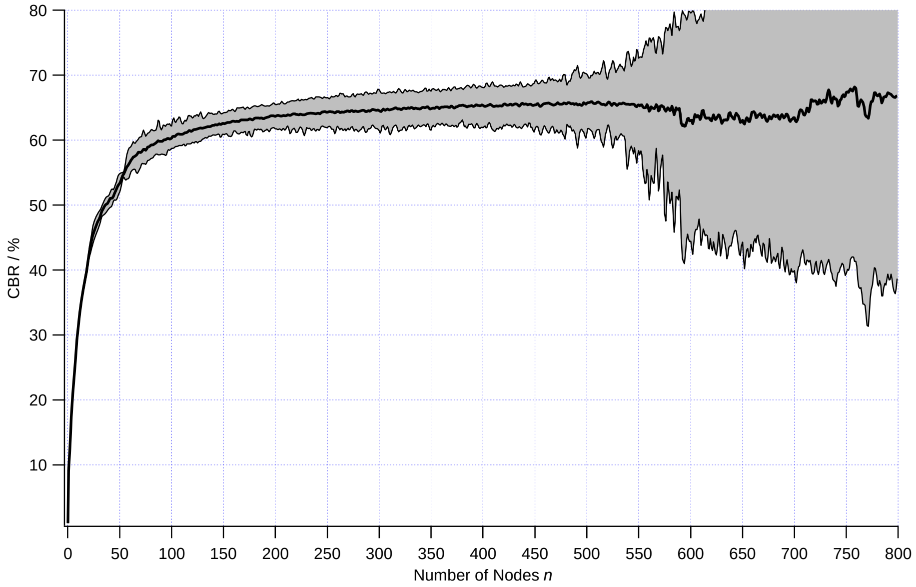


Figure D.5: Bounded stability for the adaptive DCC with α and β taken from Table 3 in ETSI TS 102 687 [i.14] for T_{on} = 1 ms and 100 ms CBR measurement time

Figure D.6 shows as an example the convergence of the CBR over time for 100 network nodes and a T_{on} of 1 ms. The black line shows the CBR measured by the network nodes and the coloured line shows the CBR average over 1 second. The coloured bars at the bottom show the transmission events of the network nodes. They are randomly distributed as expected.

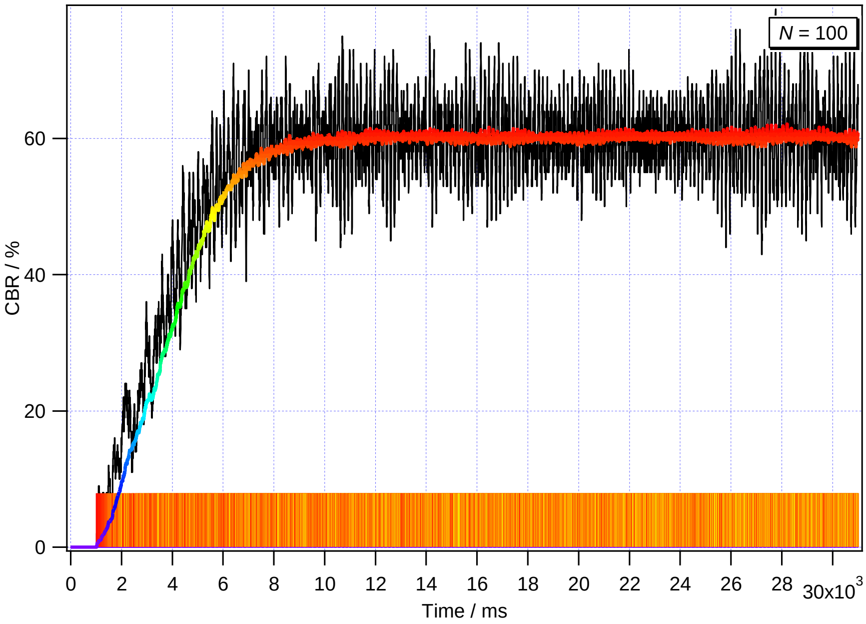


Figure D.6: CBR convergence for the adaptive DCC with α and β taken from Table 3 in ETSI TS 102 687 [i.14] for 100 nodes, T_{on} = 1 ms, and 100 ms CBR measurement time

Figure D.7 shows the T_{off} variations between 100 different network nodes for T_{on} = 1 ms. The light grey shaded region marks the ± sigma range, the dark grey region shows the minimum to maximum range of T_{off}. For all 100 nodes T_{off} converges within 30 seconds to the same equilibrium.

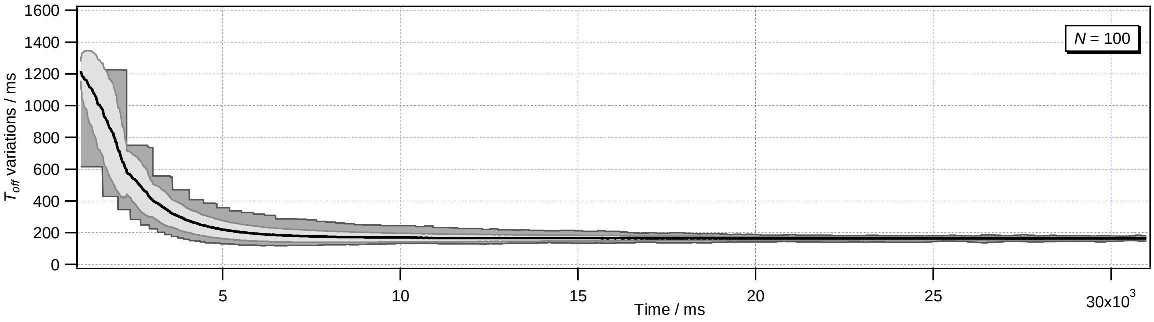


Figure D.7: T_{off} convergence for the adaptive DCC with α and β taken from Table 3 in ETSI TS 102 687 [i.14] for 100 nodes, T_{on} = 1 ms and 100 ms CBR measurement time

Figure D.8 shows what happens for a fixed 100 ms CBR measurement time when $N \times T_{off}$ is increased to 600 ms. The measured CBR shown as black line is oscillating. Also, the 1 second average shows a strong stable oscillation with CBR values between 45 % and 80 % after 30 seconds as also shown in Figure D.5. The coloured bars at the bottom of Figure D.8 show the transmission events of the network nodes. They are randomly distributed, what means that the oscillations are generated by the whole assemble of the network nodes.

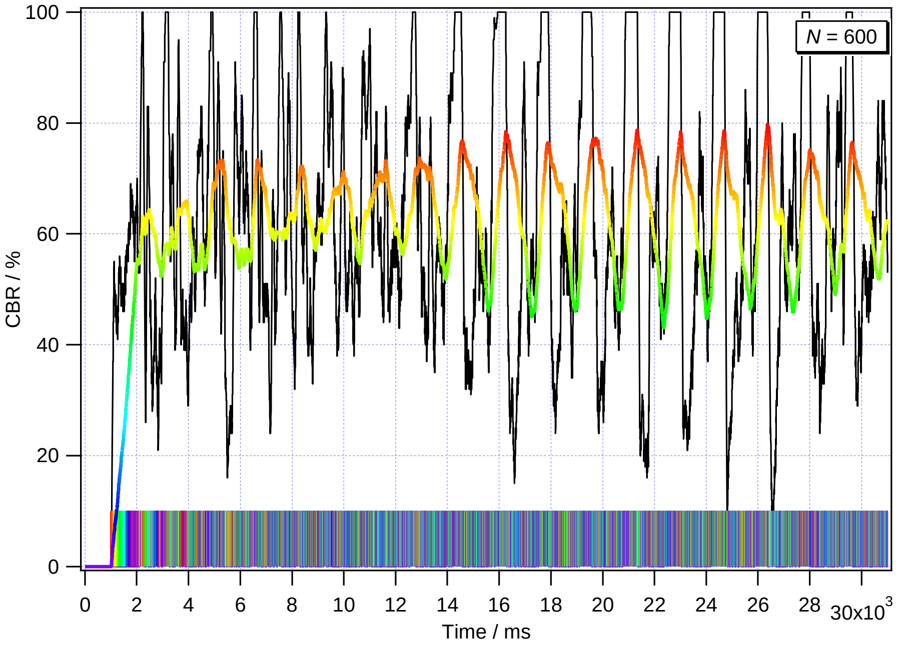


Figure D.8: CBR convergence for the adaptive DCC with α and β taken from Table 3 in ETSI TS 102 687 [i.14] for 600 nodes, T_{on} = 1 ms, and 100 ms CBR measurement time

Figure D.9 shows the T_{off} variations between the network nodes for node numbers up to 800 and T_{on} = 1 ms evaluated between 20 seconds and 30 seconds after the CBR step function. The light grey shaded region marks the ± sigma range, the dark grey region shows the minimum to maximum range of T_{off}. For more than 100 nodes the T_{off} values of the individual nodes start to diverge, even the average CBR shown in Figure D.5 converges. This is because the time constant for the T_{off} convergence is longer than the 30 second observation time. For around more than 200 nodes a T_{off} runoff of some individual nodes can be observed. A few nodes were increasing the T_{off} value to large numbers, so that they were far off the 100 ms measurement time interval and could not be recognized by the other network nodes. This effect gets even worse when the average CBR starts to oscillate.

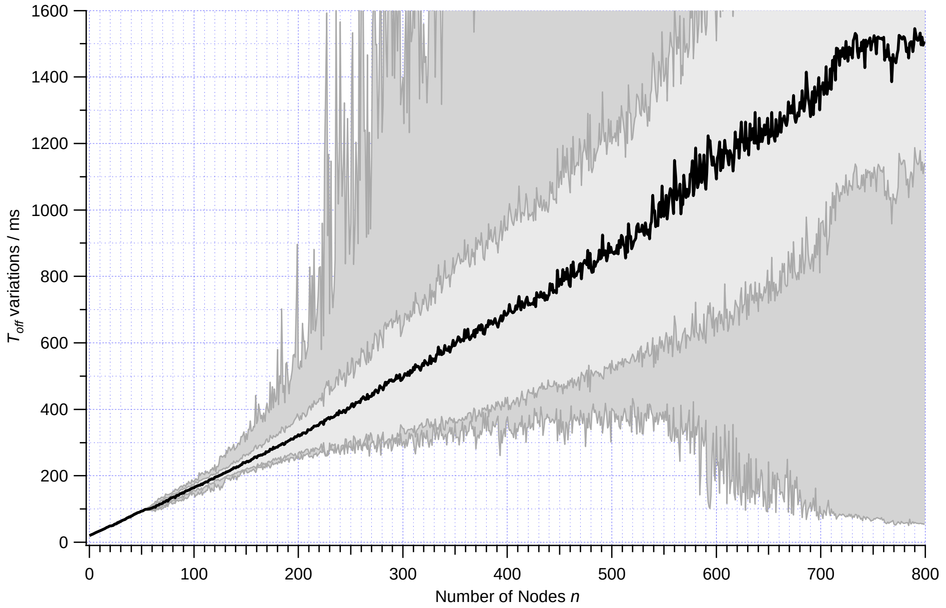


Figure D.9: T_{off} variations for the adaptive DCC with α and β taken from Table 3 in ETSI TS 102 687 [i.14] for T_{on} = 1 ms and 100 ms CBR measurement time

D.3.2 CBR measurement with a fixed 100 ms measurement time interval and a limited T_{off} range

Figure D.9 shows for the adaptive DCC with α and β taken from Table 3 in ETSI TS 102 687 [i.14] that the T_{off} values of some individual network nodes can get out of control. This can be avoided when pinning T_{off} to a maximum value when the adaptive algorithm tries to exceed a certain T_{off} range. A reasonable value for this upper T_{off} limit $T_{off\,max}$ is 1 second.

Frequency regulation assumes that the duty cycle of ITS transmissions does not exceed 1 %, this requirement gives a lower limit for T_{off}. For T_{on} = 1 ms this limit $T_{off\,min}$ results to 99 ms.

In Figure D.10 can be seen for the same α and β that this T_{off} limitation avoids excessive oscillations of the 1 second average of the CBR as was shown in Figure D.5. Nevertheless, when looking at the CBR convergence for 400 nodes in Figure D.11 it can be seen that the measured CBR over 100 ms shown as black line exhibits a strong stable oscillation up to 100 % CBR.

Figure D.12 shows the T_{off} variations between 400 different network nodes for T_{on} = 1 ms. The light green shaded region marks the ± sigma range, the dark green region shows the minimum to maximum range of T_{off}. It is obvious, that the T_{off} values do not converge at all. This can also be seen in Figure D.13 where for high node numbers the T_{off} values are even within the full range between $T_{off\,min}$ and $T_{off\,max}$.

Figure D.13 shows the T_{off} variations between the network nodes for node numbers up to 800 and T_{on} = 1 ms evaluated between 20 seconds and 30 seconds after the CBR step function. The light green shaded region marks the ± sigma range, the dark green region shows the minimum to maximum range of T_{off}. For more than 100 nodes the T_{off} values of the individual nodes start to diverge. This is because the time constant for the T_{off} convergence is longer than the 30 second observation time. For around more than 200 nodes a T_{off} runoff of some individual nodes can be observed. A few nodes were increasing the T_{off} value to the upper limit $T_{off\,max}$, so that they were far off the 100 ms measurement time interval and could not be recognized by the other network nodes. This effect gets even worse when the average CBR starts to oscillate.

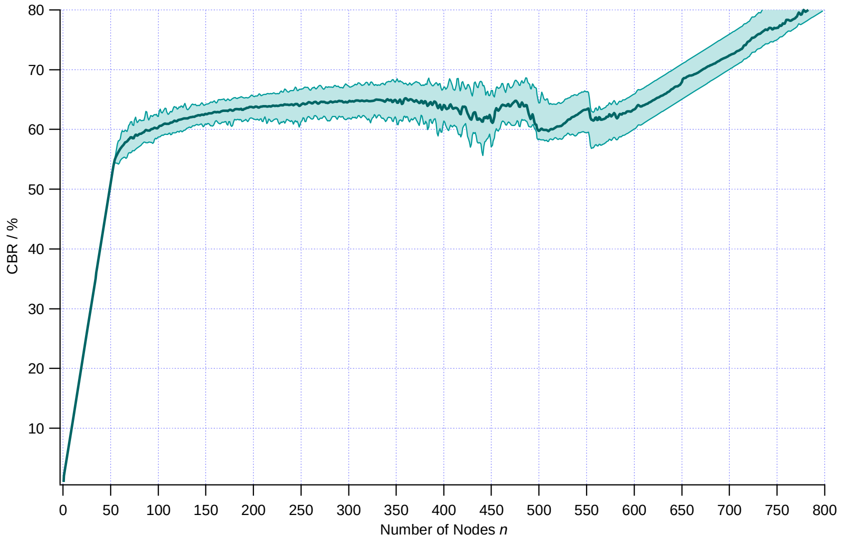


Figure D.10: Bounded stability for the adaptive DCC for a 1 % duty cycle limit, $T_{off\,max}$ = 1 s, T_{on} = 1 ms and 100 ms CBR measurement time

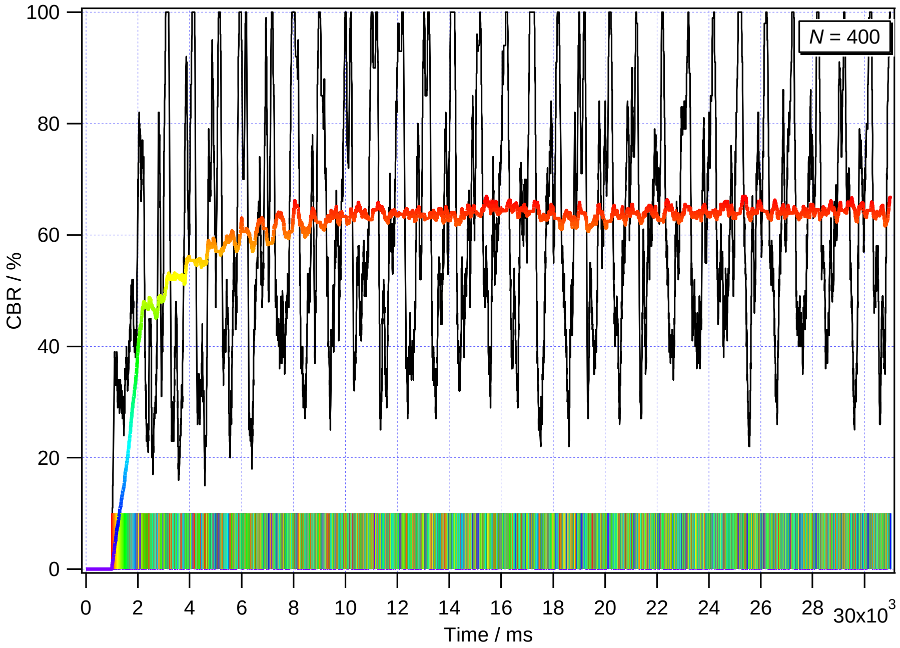


Figure D.11: CBR convergence for the adaptive DCC for 400 nodes, a 1 % duty cycle limit, $T_{off\ max}$ = 1 s, T_{on} = 1 ms, and 100 ms CBR measurement time

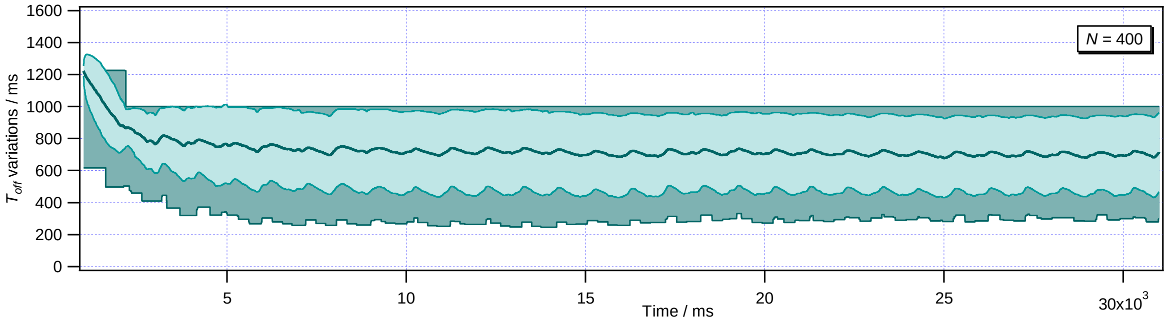


Figure D.12: T_{off} convergence for the adaptive DCC for 400 nodes, a 1 % duty cycle limit, $T_{off\ max}$ = 1 s, T_{on} = 1 ms and 100 ms CBR measurement time

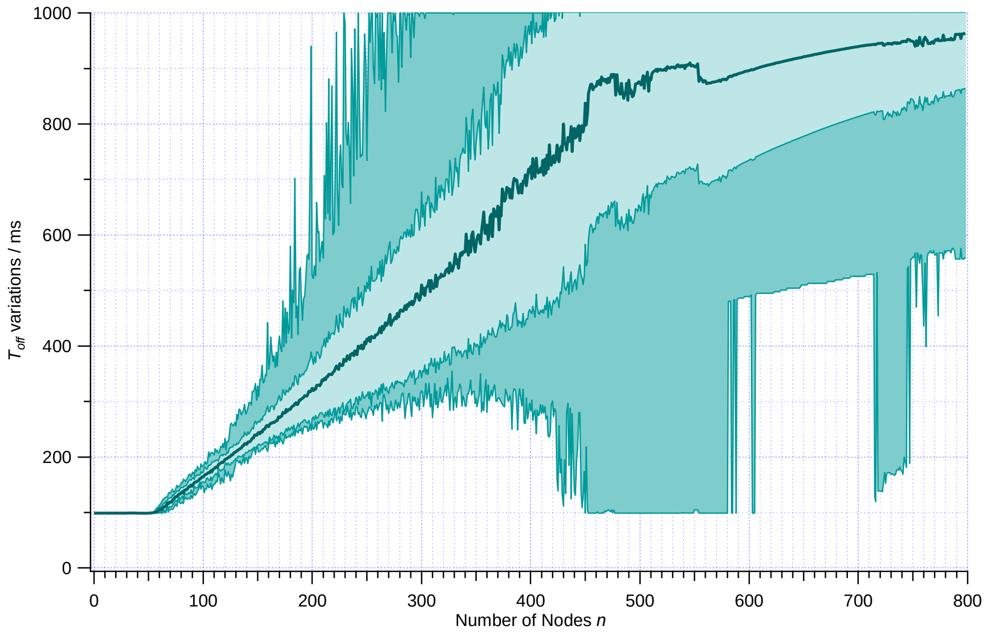


Figure D.13: T_{off} variations for the adaptive DCC for a 1 % duty cycle limit, $T_{off\,max}$ = 1 s, T_{on} = 1 ms and 100 ms CBR measurement time

D.3.3 CBR measurement and adaptive algorithm as specified in ETSI TS 102 687

ETSI TS 102 687 [i.14] specifies the $CBR_{ITS\text{-}S}$ to be taken as input for the adaptive algorithm according to equation (D.2):

$$CBR_{ITS-S}(t) = \frac{1}{2} \times \left(CBR(t) + \frac{1}{2} \times (CBR(t - 100\ ms) + CBR(t - 200\ ms)) \right) \tag{D.2}$$

Where t is the current time and $CBR(t)$ is the CBR measured over the time from t - 100 ms to t.

ETSI TS 102 687 [i.14] specifies in Table 3 the DCC algorithm parameters α, β, δ_{max}, δ_{min}, G^{+}_{max}, G^{-}_{max}, and in clause 5.4 the filter function used in this clause to evaluate the simulation results.

In addition, the T_{off} limits $T_{off\,max}$ = 1 s and $T_{off\,min}$ = 99 ms were used in the simulation with T_{on} = 1 ms.

Figure D.14 shows no significant improvement compared to Figure D.10. The improvement by averaging 3 consecutive CBR measurements can be seen when comparing Figure D.15 with Figure D.13.

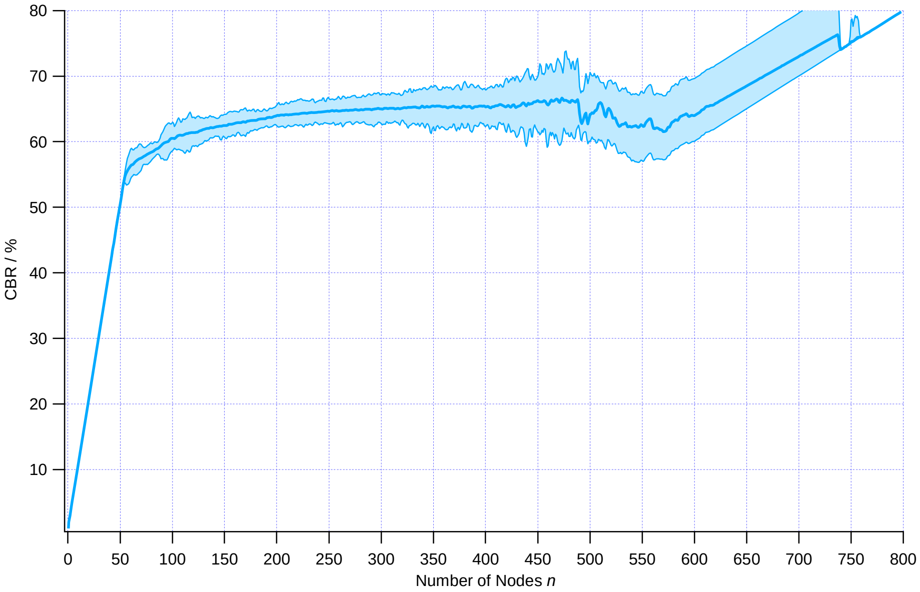


Figure D.14: Bounded stability for the adaptive DCC with a 1 % duty cycle limit, $T_{off\ max}$ = 1 s, T_{on} = 1 ms, and 100 ms CBR measurement time

Figure D.15 shows the T_{off} variations between the network nodes for node numbers up to 800 and T_{on} = 1 ms evaluated between 20 seconds and 30 seconds after the CBR step function. The light blue shaded region marks the ± sigma range, the dark blue region shows the minimum to maximum range of T_{off}. For more than 200 nodes the T_{off} values of the individual nodes start to diverge. This is because the time constant for the T_{off} convergence is longer than the 30 second observation time. For around more than 300 nodes a T_{off} runoff of some individual nodes can be observed. A few nodes were increasing the T_{off} value to the upper limit $T_{off\ max}$, so that they were off the measurement time interval of 3 times 100 ms and could not be recognized by the other network nodes. This effect gets even worse when the average CBR starts to oscillate for configurations with more than around 400 network nodes.

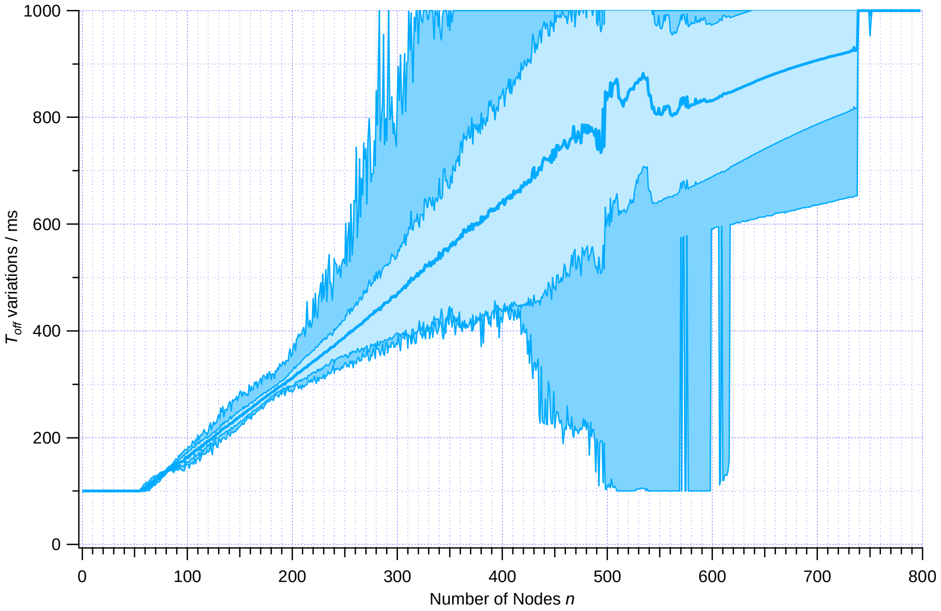


Figure D.15: T_{off} variations for the adaptive DCC with a 1 % duty cycle limit, $T_{off\ max}$ = 1 s, T_{on} = 1 ms, and 100 ms CBR measurement time

Figure D.16 shows the T_{off} variations between 300 different network nodes for T_{on} = 1 ms. The light blue shaded region marks the ± sigma range, the dark blue region shows the minimum to maximum range of T_{off}. The T_{off} value slowly converge to a common equilibrium while for 400 network nodes as shown in Figure D.17 no such convergence is observable within 30 seconds.

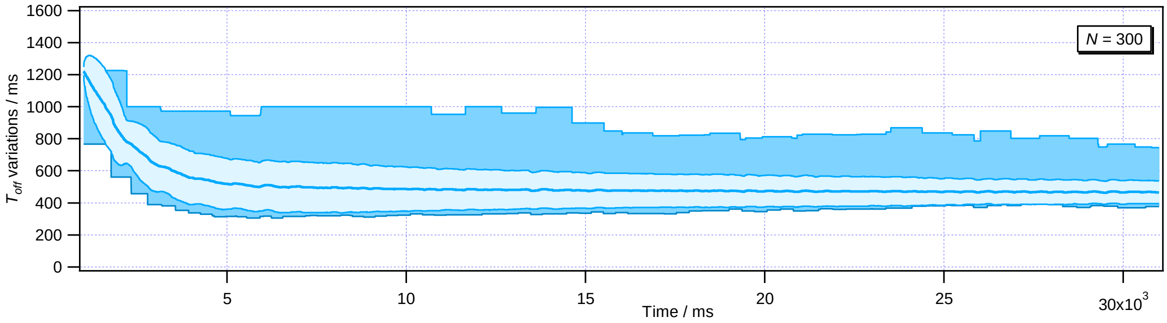


Figure D.16: T_{off} convergence for the adaptive DCC for 300 nodes, a 1 % duty cycle limit, $T_{off\ max}$ = 1 s, T_{on} = 1 ms, and 100 ms CBR measurement time

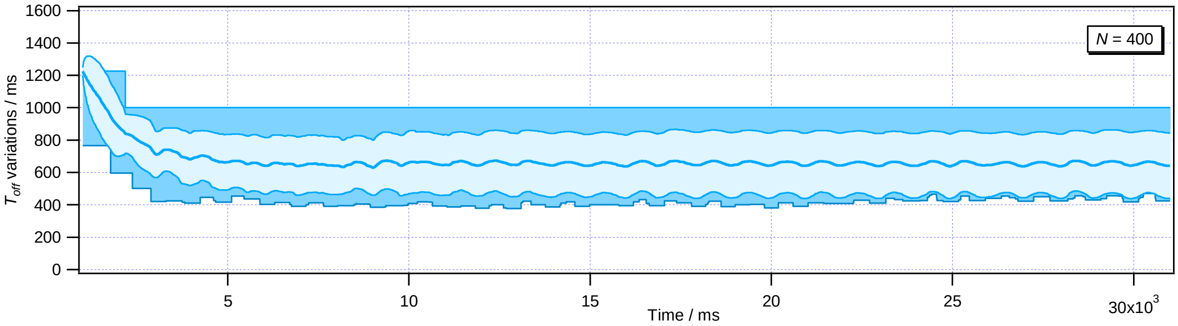


Figure D.17: T_{off} convergence for the adaptive DCC for 400 nodes, a 1 % duty cycle limit, $T_{off\ max}$ = 1 s, T_{on} = 1 ms, and 100 ms CBR measurement time

D.3.4 Dynamic CBR measurement time and adaptive algorithm as specified in ETSI TS 102 687

As outlined in clause D.1 and D.2 the CBR measurement time should be $T_{on} + T_{off}$. The results presented in clause D.3.4 were obtained by averaging the CBR over $T_{on} + T_{off}$ instead of the 100 ms measurement interval with the filtering given in ETSI TS 102 687 [i.14]. The parameters α, β, δ_{max} and δ_{min} were taken from table 3 in ETSI TS 102 687 [i.14], G^{+}_{max}, and G^{-}_{max} were not used. The T_{off} limits were $T_{off\ max}$ = 1 s and $T_{off\ min}$ = 99 ms, and T_{on} was set to 1 ms.

Figure D.18 shows only small CBR variations in the time window of 10 seconds length starting 20 seconds after the channel load step for all node numbers between 0 and 800. Figure D.19 confirms that T_{off} for all nodes is bounded in a defined range given by the convergence time.

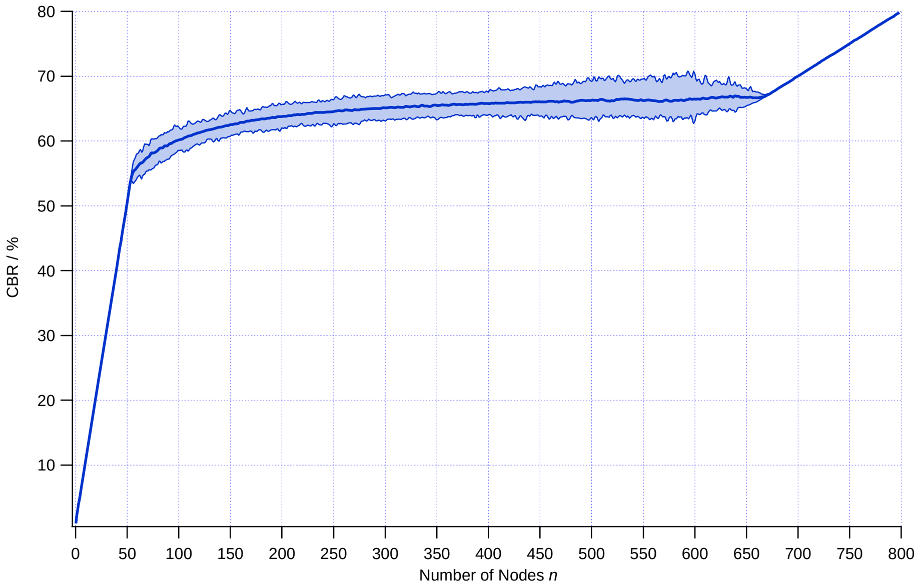


Figure D.18: Bounded stability for the adaptive DCC with a 1 % duty cycle limit, $T_{off\ max}$ = 1 s, T_{on} = 1 ms, no gain saturation, and a CBR measurement time of T_{on} + T_{off}

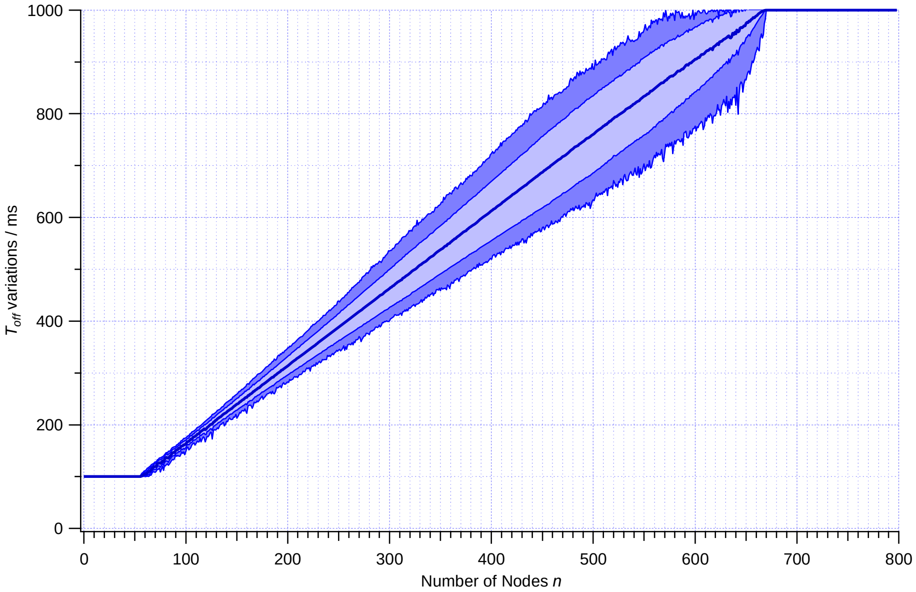


Figure D.19: T_{off} variations for the adaptive DCC with a 1 % duty cycle limit, $T_{off\ max}$ = 1 s, T_{on} = 1 ms, no gain saturation, and a CBR measurement time of T_{on} + T_{off}

Figure D.20 shows as an example that for 550 network nodes the CBR is converging to an equilibrium value. Figure D.21 shows that the convergence time of the T_{off} values for 550 network nodes exceeds 30 seconds.

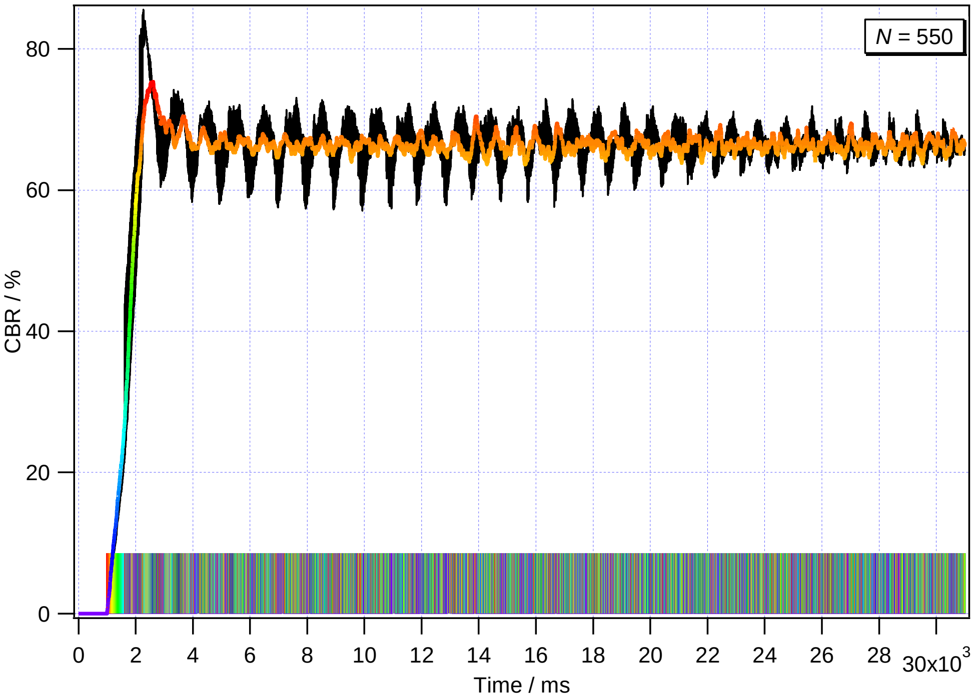


Figure D.20: CBR convergence for the adaptive DCC for 550 nodes, a 1 % duty cycle limit, $T_{off\ max}$ = 1 s, T_{on} = 1 ms, no gain saturation, and a CBR measurement time of T_{on} + T_{off}

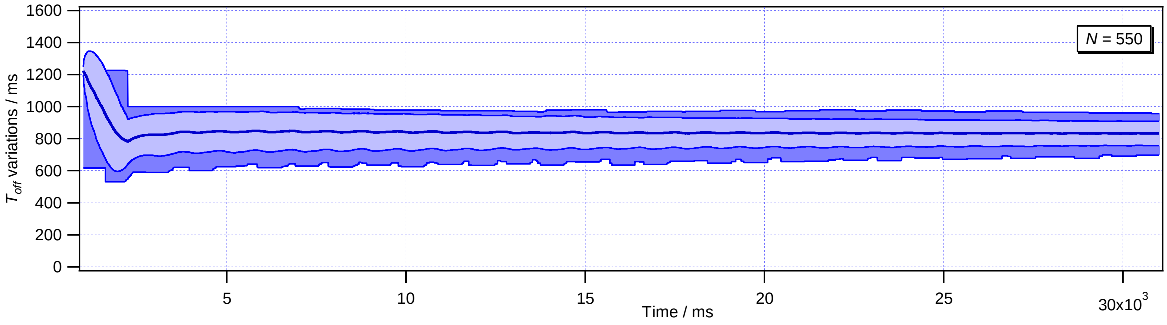


Figure D.21: T_{off} convergence for the adaptive DCC for 550 nodes, a 1 % duty cycle limit, $T_{off\ max}$ = 1 s, T_{on} = 1 ms, no gain saturation, and a CBR measurement time of T_{on} + T_{off}

D.3.5 Dynamic CBR measurement with enhanced filtering and adaptive algorithm as specified in ETSI TS 102 687

The results can be further improved when using a weighted average to determine the $CBR_{ITS\text{-}S}$ over a time span of T_{on} + T_{off}. Equation (D.3) shows such a weighted average, where $CA_{fn}(n)$ is a function that is 1 when the channel is active and 0 when it is free.

$$CBR_{ITS-S}(t) = \frac{1}{T_{on}+T_{off}}\left(0{,}95 \times \int_{t-T_{on}-T_{off}}^{t} CA_{fn}(n)dn + 0{,}1 \times \int_{t-\frac{1}{2}\times(T_{on}+T_{off})}^{t} CA_{fn}(n)dn\right) \quad \text{(D.3)}$$

When using the weighted average filter for the same configuration as given in clause D.3.4 the results can be slightly improved compared to the ones given in clause D.3.4 as shown in Figure D.22, Figure D.23, Figure D.24, and Figure D.25.

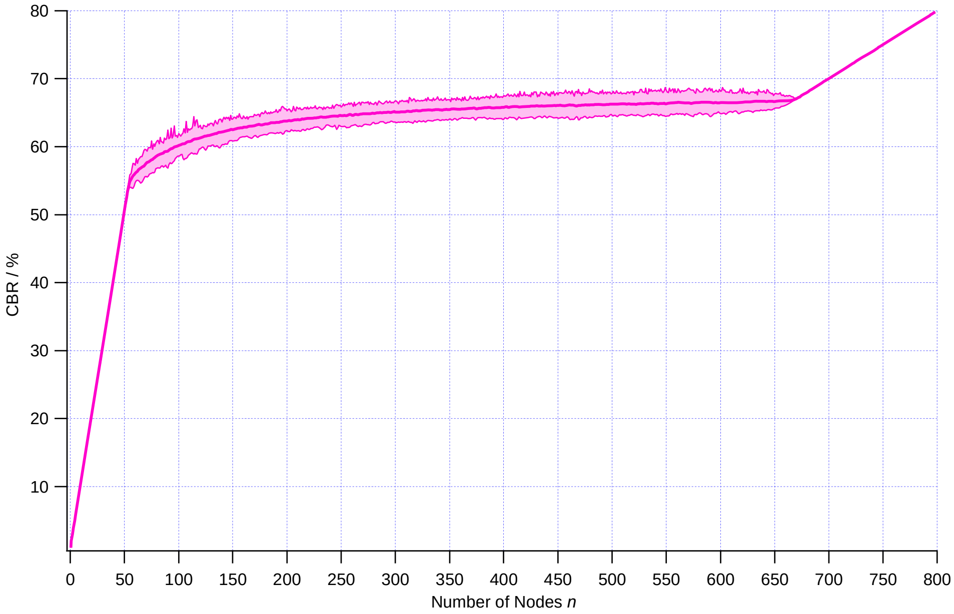


Figure D.22: Bounded stability for the adaptive DCC for a 1 % duty cycle limit, $T_{off\ max}$ = 1 s, T_{on} = 1 ms, no gain saturation, a CBR measurement time of T_{on} + T_{off}, and enhanced filtering

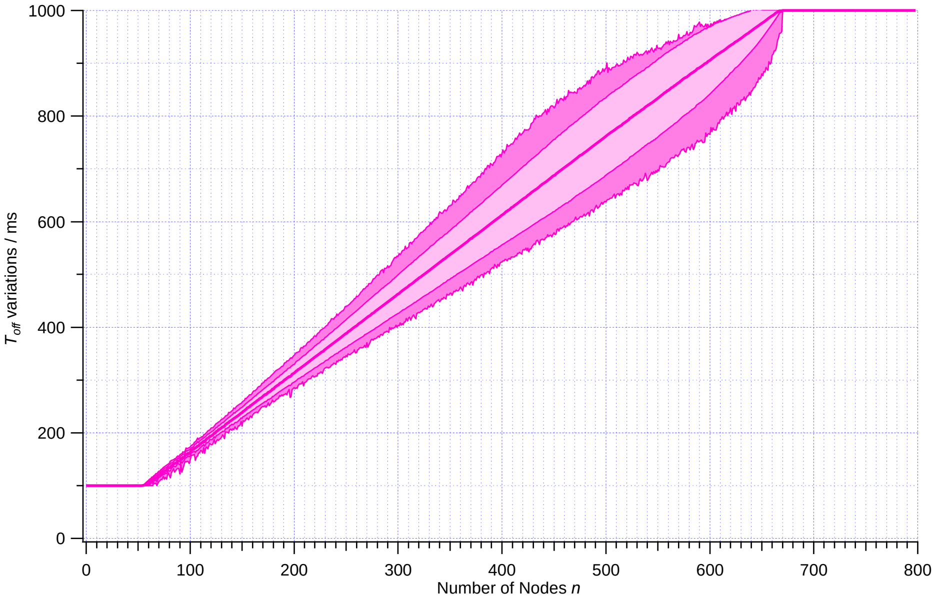


Figure D.23: T_{off} variations for the adaptive DCC with a 1 % duty cycle limit, $T_{off\ max}$ = 1 s, T_{on} = 1 ms, no gain saturation, a CBR measurement time of T_{on} + T_{off}, and enhanced filtering

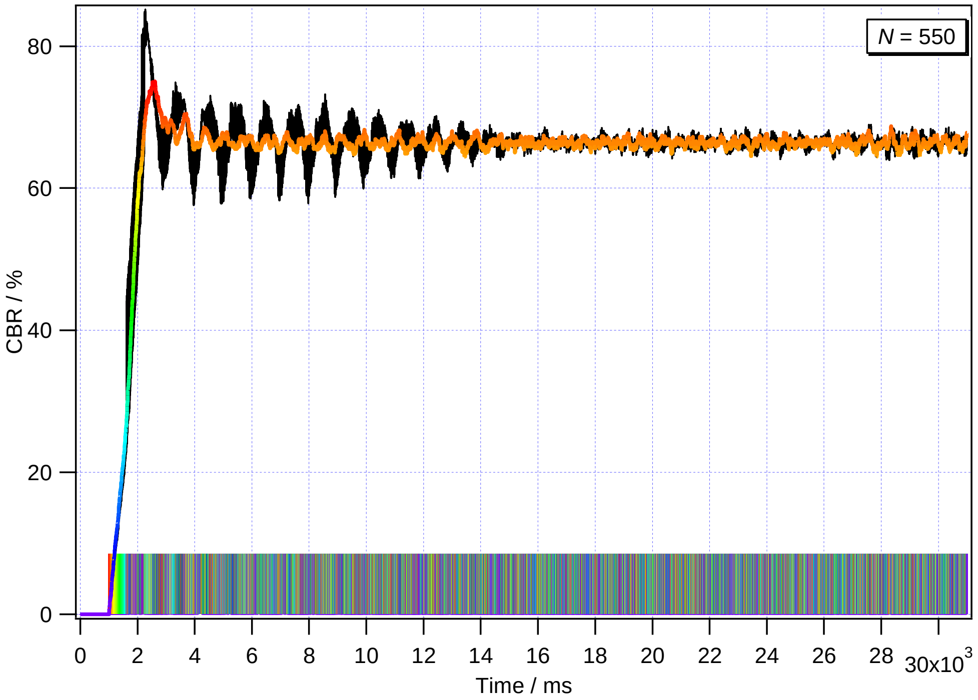


Figure D.24: CBR convergence for the adaptive DCC for 550 nodes, 1 % duty cycle limit, $T_{off\ max}$ = 1 s, T_{on} = 1 ms, no gain saturation, a CBR measurement time of T_{on} + T_{off}, and enhanced filtering

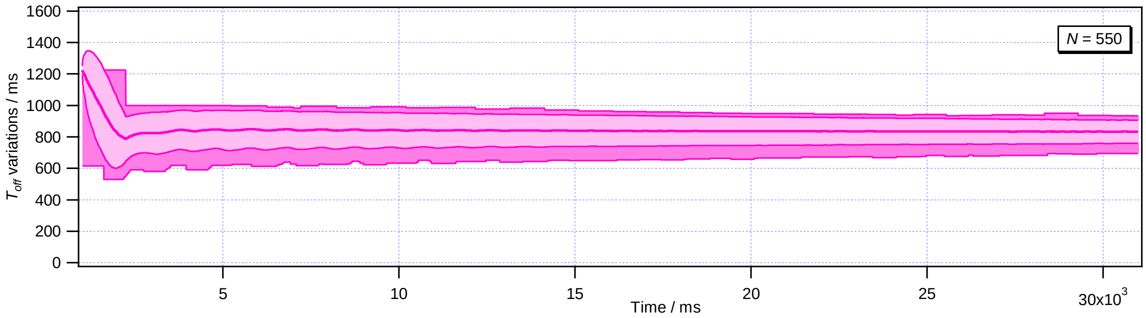


Figure D.25: T_{off} convergence for the adaptive DCC for 550 nodes, 1 % duty cycle limit, $T_{off\ max}$ = 1 s, T_{on} = 1 ms, no gain saturation, a CBR measurement time of T_{on} + T_{off}, and enhanced filtering

D.4 Influence of the MAC on the adaptive congestion control

In the previous clauses an ideal MAC was assumed that avoids packet collisions by always looking for an empty time slot to transmit. The MAC of ITS-G5 choses for each transmission a random number between 0 and 15 and counts it down as long as a time slot (contention window) is occupied on the radio channel. When this counter reaches zero or the time slot is empty, the packet is transmitted. This behaviour can lead to packet collisions, when two or more ITS-S start to transmit at the same time. These transmissions interfere with each other, and only stations close to the transmitter can receive them correctly. For random uncorrelated transmissions and low channel load the ITS-G5 MAC can efficiently avoid such collisions. Therefore, a working DCC limits the channel load and keeps the transmissions random. In the previous clauses it was shown that the transmissions can synchronize with each other, leading to an oscillating channel load. Hence, even the average of the channel load is low, short term channel congestion can happen.

Figure D.26 shows as black line the short term CBR taken as DCC input for the DCC parameters specified in ETSI TS 102 687 [i.14] for 600 ITS-S. While the short term CBR is oscillating between 45 % and 90 %, the average channel load over one second shown as coloured line is quite stable between 62 % and 69 % after a steady state is reached. Still a lot of packet collisions occur, shown as coloured bars in Figure D.26. The hight of the bars represent the number of simultaneous transmissions.

In contrast, Figure D.27 shows less packet collisions for the same DCC parameters but a dynamic CBR measurement with enhanced filtering as described in clause D.3.5 with an ITS-G5 MAC.

To reduce the packet collision rate further, either the equilibrium channel load could be lowered or the contention window counter increased. Figure D.28 shows the result for the same DCC parameters that were used to generate Figure D.27 for a MAC that is using a contention window counter range of 0 to 127 compared to 0 to 15 used for Figure D.27. This increase of the number of contention windows has no significant impact on the convergence, but it reduces the number of packet collisions drastically as shown in Figure D.29. There the difference between the packet collision ratio for an adaptive DCC with dynamic CBR measurement and enhanced filtering as described in clause D.3.5 and the DCC as specified in ETSI TS 102 687 [i.14] is shown. While the ETSI adaptive DCC shows a strong increase of the collision ratio to more than 50 %, the results for the adaptive DCC with dynamic CBR measurement stay around a collision ratio of 10 % for a contention window counter value from 0 to 15. When allowing a maximum number of 128 contention window retries, the packet collision ratio stays below 1,3 % for up to 700 ITS-S.

The drawback of increasing the contention window counter is that this increases the average transmission delay. Further investigations are necessary to find the right balance between transmission delay and packet collision ratio.

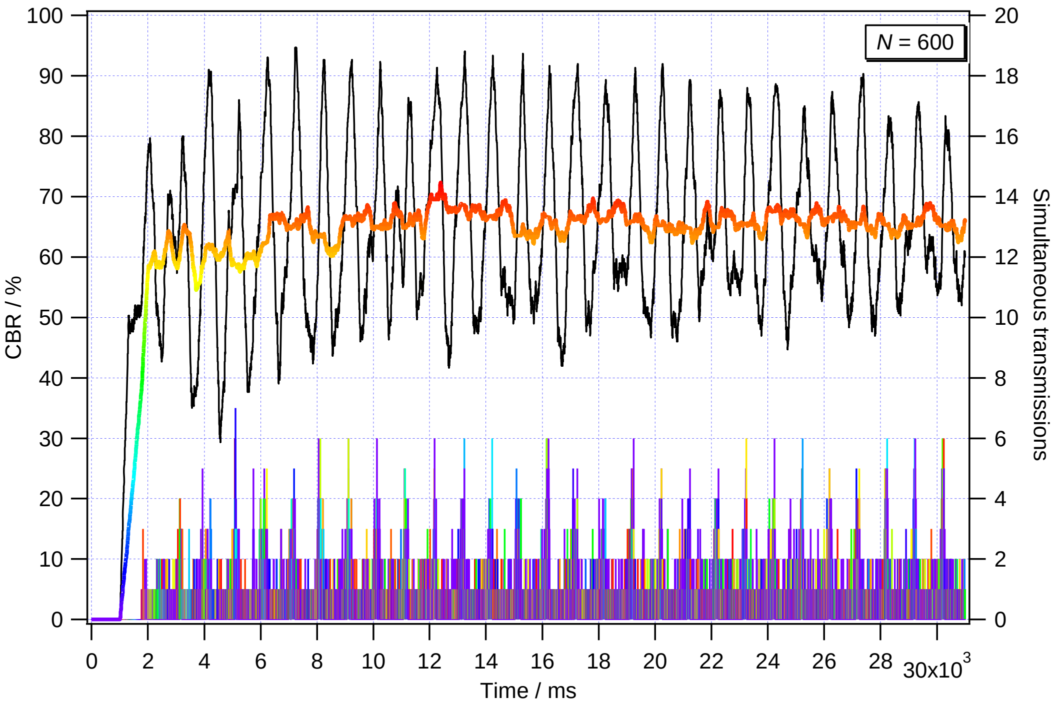


Figure D.26: CBR convergence for the adaptive DCC for 600 nodes, 1 % duty cycle limit, $T_{off\ max}$ = 1 s, T_{on} = 1 ms and the number of simultaneous transmissions for each time step for an ITS-G5 MAC

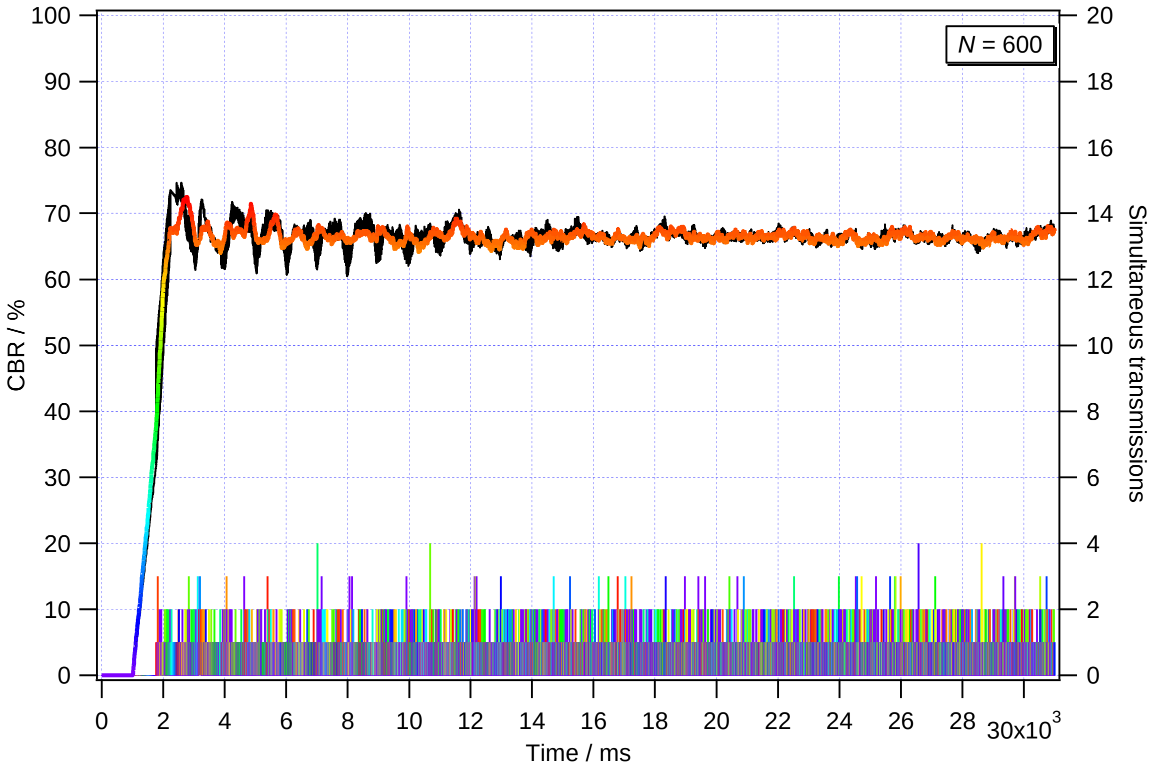


Figure D.27: CBR and number of simultaneous transmissions for the same setup as in Figure D.26 with additional gain saturation, enhanced filtering, and a CBR measurement time of T_{on} + T_{off},

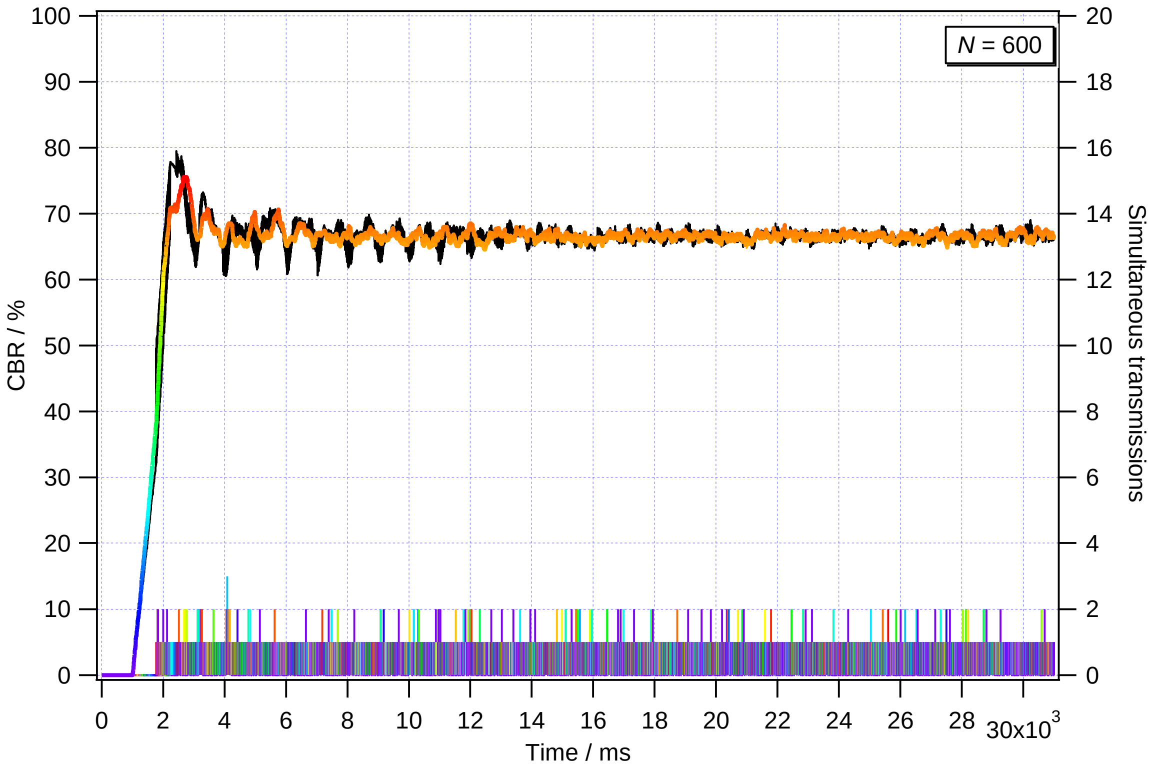


Figure D.28: CBR and number of simultaneous transmissions for the same setup as in Figure D.27 for a modified MAC using a CW counter from 0 to 127

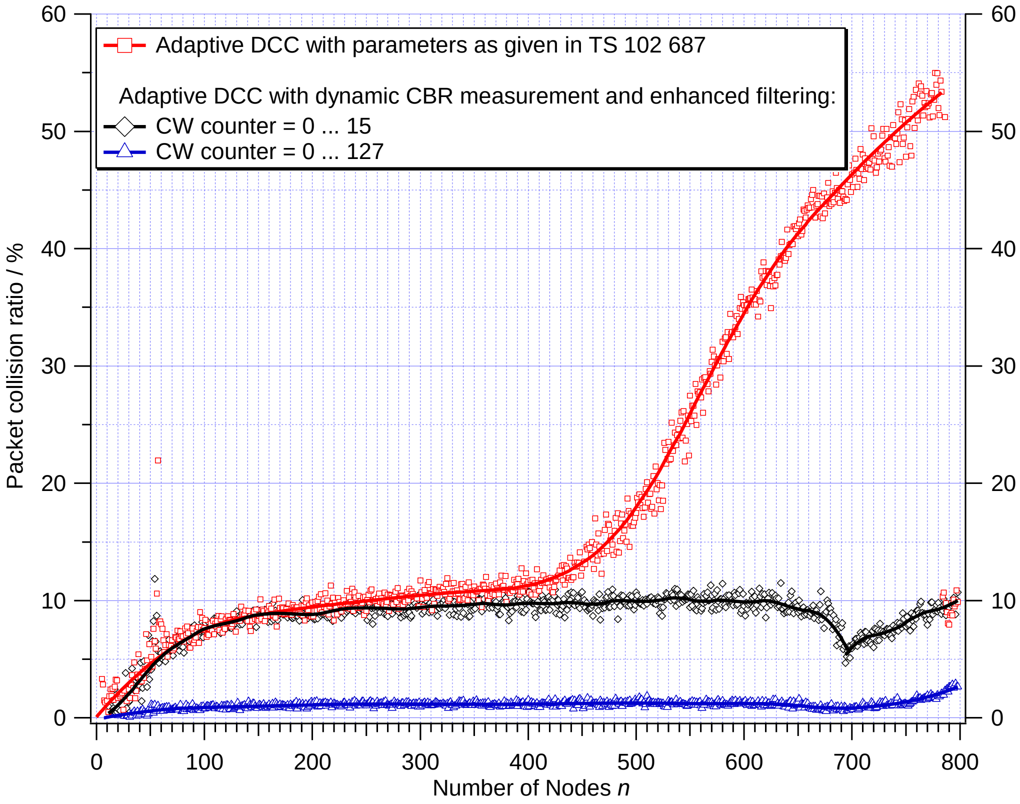


Figure D.29: Packet collision ratio for different DCC and MAC configurations

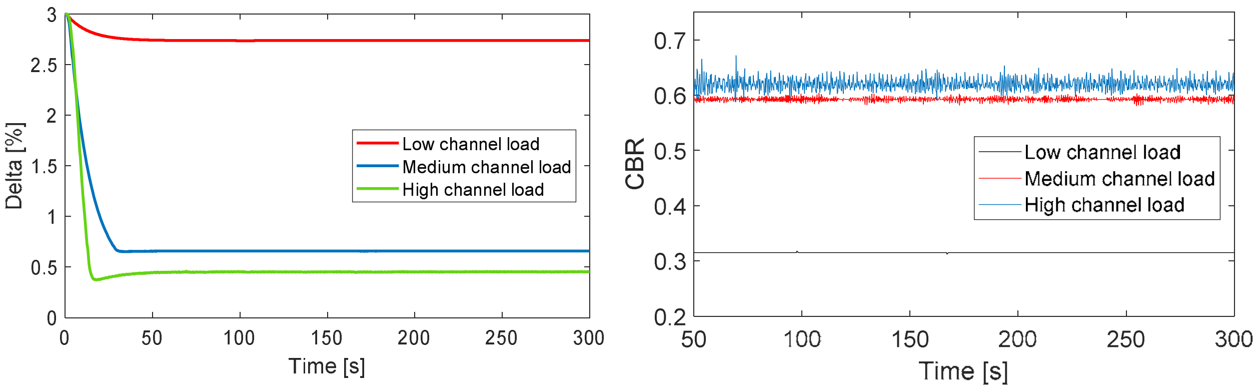
Annex E:
A real-time evaluation of basic resource management solution

E.1 Evaluation set-up

The basic solution described in clause 7.5 is evaluated. The evaluation was performed using a virtualized testing environment to mimic real-world C-ITS operations. The RM module was integrated into the Vanetza C-ITS protocol stack at the FL with only minimal modifications - leveraging an extended version of the Socktapp tool - to support the additional congestion control functionalities at the FL. To enable concurrent testing, the entire stack was encapsulated in a Docker container image, allowing multiple instances to run on a single hardware platform. Each container represented a distinct C-ITS station with five active Message services, connected via a Docker virtual network. A scaling factor was applied to emulate low, medium, and high channel load scenarios by adjusting the effective channel load, evaluated through the Channel Busy Ratio (CBR). This approach also took into account realistic processing delays and hardware limitations, ensuring that the evaluation reflected operational conditions.

E.2 Results

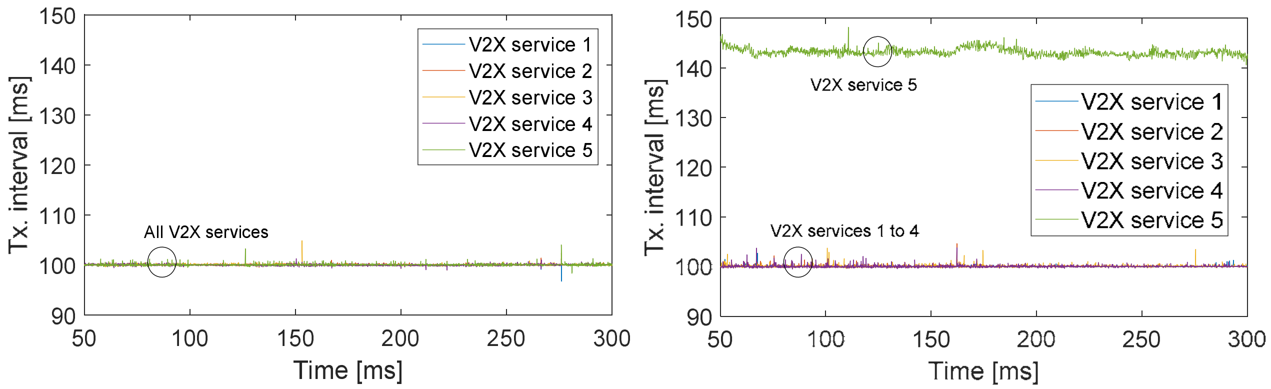
The experimental results confirmed that the basic solution achieves convergence and effective congestion control under varying channel loads. Under low channel load conditions, the system converged to a resource usage value (δ) of approximately 2,74 % (Figure E.1(a)). In contrast, for medium and high channel load scenarios, δ stabilized at around 0,66 % and 0,45 %, respectively. The evaluation showed that the implemented RM module could reduce the CBR from a potential 94 % - if all Message services transmitted at maximum rate - to about 62 % under high load (Figure E.1(b)). Additionally, while there were slight deviations between the configured and actual transmission intervals (attributable to real-time processing delays, see Figure E.2, these discrepancies did not impact the overall stability or robustness of the congestion control mechanism. The results validate that the integration of the RM within Vanetza and its execution in a Docker-based virtualized environment effectively bridge simulation-based studies and real-world testing.



(a) Available resources (delta)

(b) Channel load or CBR (Channel Busy Ratio)

Figure E.1: Stability and convergence of the implementation



(a) Low channel load

(b) Medium channel load

Figure E.2: Time evolution of transmission interval of different Message services

Annex F:
Maximum size of Facilities layer message size

For transmission of FL messages over ITS-G5, Release 1 considers the maximum size of these messages. Two main reasons for message size limitation exist:

- Existing specifications from lower layer standards, specifically PHY, MAC, LLC.
- Radio performance considerations.

From an ITS-G5 PHY perspective, the size of a PHY frame is limited by the 12-bit PHY header "Length" field, which results in a maximum PHY frame size 4 095 Bytes.

From an ITS-G5 MAC perspective, the MTU corresponds to the maximum MSDU as defined in IEEE 802.11 [i.9], i.e. the payload that higher layers deliver to the IEEE 802.11 MAC layer, and equals 2 304 Bytes. This MTU is further reduced by LLC with the SNAP option, GeoNetworking and BTP headers, yielding a theoretical maximum FL message size of 2 252 Bytes (see Table 3, column non-NGV ITS-G5), which still need to be reduced by the variable size of signature and certificate (see also clause 5.5.5). In comparison to the non-NGV ITS-G5, the NGV ITS-G5 allows a larger MTU size, which results in a maximum FL-SDU size of 7 883 Bytes, minus size of signature and certificate (see column NGV ITS-G5 in Table 3).

Table 3: Maximum FL message size for ITS-G5 without consideration of size for signature and certificate

	Ethertype-compatible ITS-G5	non-NGV ITS-G5	NGV ITS-G5
MTU (max MSDU)	1 500 B	2 304 B	7 935 B
LLC (802.2 LLC + SNAP)	- 8 B	- 8 B	- 8 B
GeoNetworking Header	- 88 B (maximum)	- 40 B (SHB)	- 40 B (SHB)
BTP-Header	- 4 B	- 4 B	- 4 B
Maximum FL-SDU	1 400 B	2 252 B	7 883 B

Another consideration in the message size is the convention that in IEEE 802.11 networks, IP typically sets the MTU size to 1 500 Bytes (see IETF RFC 1042 [i.48]). It is important to emphasize that the 1 500 Bytes limitation does not originate from the IEEE 802.11 standard but has historical reasons: When Wi-Fi® emerged as a wireless LAN technology, it was designed to interoperate transparently with wired Ethernet networks - using the same IP subnet, Layer-2 bridging, and protocol stack without additional configuration. To maintain this compatibility, implementors adopted Ethernet's maximum payload size of 1 500 Bytes, even though the IEEE 802.11 MAC technically allows a MSDU of up to 2 304 Bytes. This line of argumentation was used in Release 1 to effectively limit the maximum FL message in Release 1 to 1 400 Bytes, minus size of signature and certificate (see Table 3, column Ethertype-compatible ITS-G5). For Release 2, stakeholders in TC ITS should be consulted whether the argumentation for the 1 500 Bytes still applies for Release 2 implementations or whether a larger size can be permitted.

For LTE-V2X and 5G NR-V2X, an equivalent analysis of the maximum FL message size is not feasible because the PC5 interface does not define a fixed MTU at layer 2. Instead, data is segmented into MAC SDUs, which are then mapped into so-called Transport Blocks (TBs). The size of a TB is determined by the selected MCS, the available bandwidth, and the allocated radio resources, rather than by any fixed limit.

In defining the maximum FL message size, radio-related aspects should be considered. In practice, the transmission of large frames may suffer from synchronization and equalization issues, particularly at high vehicle speeds.

Since different access-layer technologies exhibit different physical-layer capabilities, the maximum FL message size may also differ across these technologies. For example, a larger FL message size may be feasible for NGV ITS-G5 than for 11p-mode, taking into account the improved radio performance of NGV ITS-G5 - such as wider 20 MHz channels (instead of 10 MHz), the use of mid-ambles (instead of preambles only), and improved channel coding.

Consequently, a maximum FL message size could be set that is lower than the theoretical values in Table 3, representing a compromise between maximizing application payload and minimizing adverse radio effects.

History

Version	Date	Status
V2.1.1	July 2025	Publication
V2.2.1	February 2026	Publication