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**Broadband Radio Access Networks (BRAN);
5 GHz high performance RLAN;
Mitigation techniques to enable sharing between RLANs
and Road Tolling and Intelligent Transport Systems
in the 5 725 MHz to 5 925 MHz band**

Reference
DTR/BRAN-60018

Keywords
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Foreword

This Technical Report (TR) has been produced by ETSI Technical Committee Broadband Radio Access Networks (BRAN).

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 contains mitigation technique studies related to RLANs in the 5 795 MHz to 5 815 MHz and 5 855 MHz to 5 925 MHz frequency ranges. These have been triggered by the EC Mandate on 5 GHz [i.1] and by the activities on WRC-15 Agenda Item 1.1 [i.49] and subsequent work at CEPT. In particular CEPT have requested clarification on what mitigation techniques RLAN systems intend to employ to protect other systems that presently operate in the 5 725 MHz to 5 925 MHz band and in adjacent bands.

Some of the parameters within the present document are included in square brackets based upon proposals and discussions within TC BRAN, these are intended as starting points upon which to continue future work and develop technical requirements.

At the time of drafting the present document the status of the various sharing and compatibility studies related to Road Tolling and ITS is as detailed in ECC Report 244 [i.15] and is summarized below:

Compatibility between RLAN and road tolling in the band 5 795 MHz to 5 815 MHz

MCL calculations for both directions of interference have been performed and showed the need for significant separation distances if compatibility is dependent upon protection to an I/N level of -6 dB. No studies have been conducted to analyse the actual effects of this I/N level being reached due to intermittent interference.

As a result, work on mitigation techniques was initiated at ETSI BRAN which focused on the following approaches, previously suggested in ECC Report 244 [i.15], to enable the coexistence between RLAN and road-tolling:

- Implementation in RLAN of a detection mechanism to detect road tolling applications based on energy detection. Under the assumptions considered preliminary analysis indicated that for an RLAN system operating with 23 dBm/20 MHz a detection threshold of the order of -100 dBm/500 kHz and for a RLAN system with 23 dBm/160 MHz a detection threshold of the order of -90 dBm/500 kHz would be required for a reliable detection of road tolling. Further consideration is required, including on the feasibility of such a detection threshold and its impact on the RLAN operation.

- Transmission from the road tolling applications of predefined signals (beacons) which indicate that the used channels are busy, similar to one of the mitigation techniques used to facilitate ITS and Road Tolling adjacent channel coexistence.

- Ensure coexistence with the road tolling systems through the detection of ITS. This is based on the assumption that there will always be ITS systems in the close vicinity of road-tolling road-side units. Under this approach, once ITS have been detected by RLAN under the conditions described in clause 2 of ECC Report 244 [i.15], the road tolling frequency band 5 795 MHz to 5 815 MHz will also be considered as occupied and thus, not available for RLAN use.

- Use of geo-location database approach. The geo-location database should hold actual information from static and, due to construction sites, temporary tolling installations. The implementation of such a platform, its access and its maintenance should be addressed. In addition, the role and responsibilities of the stakeholders have to be clearly defined.

Compatibility between RLAN and ITS in the bands 5 855 MHz to 5 875 MHz (non-safety ITS), 5 875 MHz to 5 905 MHz (safety-related ITS) and 5 905 MHz to 5 925 MHz (ITS extension band)

Compatibility considered in the present document includes Wi-Fi and ITS technology as defined in ETSI EN 302 663 [i.3]. LTE-V2X and LAA technologies as defined in ETSI TS 136 211 [i.10], ETSI TS 136 101 [i.11] and ETSI TS 136 104 [i.12] are not part of the present document.

MCL calculations for both directions of interference have been performed and showed the need for significant separation distances if compatibility is dependent upon protection to an I/N level of -6 dB. No studies have been conducted to analyse the actual effects of this I/N level being reached due to intermittent interference.

As a result, work on mitigation techniques was initiated at ETSI BRAN to help improve the compatibility between individual RLAN devices and ITS. These studies have focussed on "listen-before-talk" processes, where the potential interferer tries to detect whether a channel is busy before transmitting a data packet.

Two possible approaches that have been suggested in ECC Report 244 [i.15] are:

- Generic Energy Detection without any consideration of the interferer and victim signal frames: Under the assumptions considered, preliminary studies show that in the case of an energy detection threshold of -90 dBm/10 MHz for an RLAN system operating with 23 dBm/20 MHz, an ITS device with 23 dBm/20 MHz is not reliably detected. Further consideration is required, including on the feasibility of such a detection threshold and its impact on the RLAN operation.

- Combination of energy detection and carrier sensing, such as one of the Clear Channel Assessment (CCA) modes defined in the IEEE Std. 802.11™-2016 [i.2]. Further study is required to assess the applicability to ITS of the interference avoidance techniques currently employed in 5 GHz RLAN systems.

Introduction

The present document studies the feasibility and impact on RLAN operation with regards to proposed mitigation techniques to enable sharing with Road Tolling and Transport equipment within the 5 795 MHz to 5 815 MHz and 5 855 MHz to 5 925 MHz frequency ranges. The report proposes and evaluates mitigation techniques based upon simulation and analytical investigation. Some of the parameters within the present document are included in square brackets based upon proposals and discussions within TC BRAN, these are intended as starting points upon which to continue future work and develop technical requirements. Recommendations for future work are included in clause 7.7.

1 Scope

The present document contains mitigation technique studies related to RLAN operation in the 5 795 MHz to 5 815 MHz and 5 855 MHz to 5 925 MHz frequency ranges. These have been triggered by the EC Mandate on 5 GHz [i.1] and by the activities on WRC-15 Agenda Item 1.1 [i.49] and subsequent work at CEPT.

Mitigation techniques between RLAN and the following equipment are considered in the present document:

- Road tolling in the bands 5 795 MHz to 5 805 MHz and 5 805 MHz to 5 815 MHz.
- Traffic safety-related applications in the band 5 875 MHz to 5 905 MHz.
- Possible Future extension of ITS spectrum in the band 5 905 MHz to 5 925 MHz. This band is proposed to be considered for safety-related ITS applications.
- Recommended for ITS non-safety applications in the band 5 855 MHz to 5 875 MHz.

The only RLAN technology considered in the present document is Wi-Fi as defined under IEEE Std. 802.11™-2016 [i.2]. The only ITS technology considered in the present document is as defined in ETSI EN 302 663 [i.3].

The present document is intended to guide further work on coexistence studies in CEPT in order to enable sharing between RLANs and other equipment using these frequency bands.

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.

NOTE: While any hyperlinks included in this clause were valid at the time of publication, ETSI cannot guarantee their long term validity.

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

[i.1] EC Mandate to CEPT on 5 GHz: "Mandate to CEPT to study and identify harmonised compatibility and sharing conditions for Wireless Access Systems including Radio Local Area Networks in the bands 5350-5470 MHz and 5725-5925 MHz ('WAS/RLAN extension bands') for the provision of wireless broadband services".

[i.2] IEEE Std. 802.11™-2016: "IEEE Standard for Information technology--Telecommunications and information exchange between systems Local and metropolitan area networks--Specific requirements - Part 11: Wireless LAN Medium Access Control (MAC) and Physical Layer (PHY) Specifications".

[i.3] ETSI EN 302 663 (V1.2.1) (07-2013): "Intelligent Transport Systems (ITS); Access layer specification for Intelligent Transport Systems operating in the 5 GHz frequency band".

[i.4] Commission Decision 2005/513/EC of 11 July 2005 on the harmonised use of radio spectrum in the 5 GHz frequency band for the implementation of wireless access systems including radio local area networks (WAS/RLANs). .

[i.5] Commission Decision 2007/90/EC of 12 February 2007 amending Decision 2005/513/EC on the harmonised use of radio spectrum in the 5 GHz frequency band for the implementation of Wireless Access Systems including Radio Local Area Networks (WAS/RLANs).

[i.6] ECC/DEC/(04)08: "ECC Decision of 9 July 2004 on the harmonised use of the 5 GHz frequency bands for the implementation of Wireless Access Systems including Radio Local Area Networks (WAS/RLANs) (30/10/2009)".

[i.7] Resolution 229: "(WRC-03, Rev. WRC-12) on the use of the bands 5150-5250 MHz, 5250-5350 MHz and 5470-5725 MHz by the mobile service for the implementation of wireless access systems including radio local area networks".

[i.8] Recommendation ITU-R M.1652: "Dynamic frequency selection in wireless access systems including radio local area networks for the purpose of protecting the radio-determination service in the 5 GHz band".

[i.9] ETSI EN 301 893 (V2.1.1) (05-2017): "5 GHz RLAN; Harmonised Standard covering the essential requirements of article 3.2 of Directive 2014/53/EU".

[i.10] ETSI TS 136 211 (V13.3.0) (11-2016): "LTE; Evolved Universal Terrestrial Radio Access (E-UTRA); Physical channels and modulation (3GPP TS 36.211 version 13.3.0 Release 13)".

[i.11] ETSI TS 136 101 (V11.17.0) (09-2016): "LTE; Evolved Universal Terrestrial Radio Access (E-UTRA); User Equipment (UE) radio transmission and reception (3GPP TS 36.101 version 11.17.0 Release 11)".

[i.12] ETSI TS 136 104 (V13.5.0) (10-2016): "LTE; Evolved Universal Terrestrial Radio Access (E-UTRA); Base Station (BS) radio transmission and reception (3GPP TS 36.104 version 13.5.0 Release 13)".

[i.13] CEPT Report 57: "Compatibility and sharing conditions for WAS/RLAN in the bands 5350-5470 MHz and 5725-5925 MHz".

[i.14] CEPT Report 64: "To study and identify harmonised compatibility and sharing conditions for Wireless Access Systems including Radio Local Area Networks in the bands 5350-5470 MHz and 5725-5925 MHz ('WAS/RLAN extension bands') for the provision of wireless broadband services".

[i.15] ECC Report 244: "Compatibility studies related to RLANs in 5725-5925 MHz".

[i.16] ECC/DEC/(02)01: "ECC Decision of 15 March 2002 on the frequency bands to be designated for the co-ordinated introduction of Road Transport and Traffic Telematic Systems".

[i.17] ECC/DEC(12)04: "ECC Decision on 02 November 2012 on the withdrawal of ECC Decision (02)01".

[i.18] Directive 2004/52/EC of the European Parliament and of the Council of 29 April 2004 on the interoperability of electronic road toll systems in the Community.

[i.19] ERC Recommendation 70-03: "Relating to the use of Short Range Devices (SRD)".

[i.20] ETSI EN 300 674-2-1 (V2.1.1) (09-2016): "Transport and Traffic Telematics (TTT); Dedicated Short Range Communication (DSRC) transmission equipment (500 kbit/s / 250 kbit/s) operating in the 5 795 MHz to 5 815 MHz frequency band; Part 2: Harmonised Standard covering the essential requirements of article 3.2 of the Directive 2014/53/EU; Sub-part 1: Road Side Units (RSU)".

[i.21] ETSI EN 300 674-2-2 (V2.1.1) (11-12016): "Transport and Traffic Telematics (TTT); Dedicated Short Range Communication (DSRC) transmission equipment (500 kbit/s / 250 kbit/s) operating in the 5 795 MHz to 5 815 MHz frequency band; Part 2: Harmonised Standard covering the essential requirements of article 3.2 of Directive 2014/53/EU; Sub-part 2: On-Board Units (OBU)".

[i.22] Commission Implementing Regulation (EU) 2016/799 of 18 March 2016 implementing Regulation (EU) No 165/2014 of the European Parliament and of the Council laying down the requirements for the construction, testing, installation, operation and repair of tachographs and their components.

[i.23] Directive (EU) 2015/719 of the European Parliament and of the Council of 29 April 2015 amending Council Directive 96/53/EC laying down for certain road vehicles circulating within the Community the maximum authorised dimensions in national and international traffic and the maximum authorised weights in international traffic.

[i.24] ETSI ES 200 674-1 (V2.4.1) (05-2013): "Intelligent Transport Systems (ITS); Road Transport and Traffic Telematics (RTTT); Dedicated Short Range Communications (DSRC); Part 1: Technical characteristics and test methods for High Data Rate (HDR) data transmission equipment operating in the 5,8 GHz Industrial, Scientific and Medical (ISM) band".

[i.25] Commission Decision 2008/671/EC of 5 August on the harmonised use of radio spectrum in the 5875-5905 MHz frequency band for safety-related application of Intelligent Transport Systems (ITS).

[i.26] ECC/REC/(08)01: "Use of the band 5855-5875 MHz for Intelligent Transport Systems (ITS)".

[i.27] Directive 2010/40/EU 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.28] M/453 Standardisation mandate addressed to CEN, CENELEC and ETSI in the field of information and communication technologies to support the interoperability of co-operative systems for Intelligent Transport in the European Community.

[i.29] ETSI TR 103 083 (V1.1.1) (03-2014): "Electromagnetic compatibility and Radio spectrum Matters (ERM); System Reference document (SRdoc); Technical characteristics for pan European harmonized communications equipment operating in the 5,855 GHz to 5,925 GHz range intended for road safety and traffic management, and for non-safety related ITS applications".

[i.30] ECC/DEC/(08)01: "ECC Decision of 14 March 2008 on the harmonised use of the 5875-5925 frequency band for Intelligent Transport Systems (ITS)", approved 14 March 2008 and amended 3 July 2015.

[i.31] ETSI EN 302 571: "Intelligent Transport Systems (ITS); Radiocommunications equipment operating in the 5 855 MHz to 5 925 MHz frequency band; Harmonized EN covering the essential requirements of article 3.2 of the R&TTE Directive".

[i.32] ECC Report 228: "Compatibility Studies between the Intelligent Transport Systems (ITS) in the Band 5 855 MHz to 5 925 MHz and other systems in adjacent bands".

[i.33] ETSI TS 102 792 (V1.2.1): "Intelligent Transport Systems (ITS); Mitigation techniques to avoid interference between European CEN Dedicated Short Range Communication (CEN DSRC) equipment and Intelligent Transport Systems (ITS) operating in the 5 GHz frequency range".

[i.34] Austrian HGV Tolling System: "EETS OBE Requirements Specification", V1.13, 2015.

[i.35] ETSI TS 102 687 (V1.1.1) (07-2011): "Intelligent Transport Systems (ITS); Decentralized Congestion Control Mechanisms for Intelligent Transport Systems operating in the 5 GHz range; Access layer part".

[i.36] ETSI TS 102 637-2: "Intelligent Transport Systems (ITS); Vehicular Communications; Basic Set of Applications; Part 2: Specification of Cooperative Awareness Basic Service".

[i.37] ETSI TS 102 894-2 (V1.2.1): "Intelligent Transport Systems (ITS); Users and applications requirements; Part 2: Applications and facilities layer common data dictionary".

[i.38] IEEE 802.11™-03/940r4: "TGn Channel Models", May 2004.

[i.39] Kenney, Barve, Rai and Kanai: "Comparing Communication Performance of DSRC OBEs from Multiple Suppliers", ITS World Congress 2012.

[i.40] ETSI TC BRAN(16)000078r2 DSRC-RLAN-mitigation-simulations, May 2016.

[i.41] ETSI TC BRAN(16)000081r3 and BRAN(16)000165 Challenges in spectrum sharing between ITS-G5 and RLAN, September 2016.

[i.42] ETSI TC BRAN(16)000138r4 RLAN-ITS-G5 Coexistence Evaluation, May 2017.

[i.43] ETSI TR 102 960 (V1.1.1) (11-2012): "Intelligent Transport Systems (ITS);Mitigation techniques to avoid interference between European CEN Dedicated Short Range Communication (RTTT DSRC) equipment and Intelligent Transport Systems (ITS) operating in the 5 GHz frequency range; Evaluation of mitigation methods and techniques".

[i.44] Mangel, T., Klemp, O. and Hartenstein, H: "5.9 GHz inter-vehicle communication at intersections: a validated non-line-of-sight path-loss and fading model". EURASIP Journal on Wireless Communications and Networking, 2011(1), 1-11.

[i.45] WINNER Channel Models, WINNER II Project, D1.1.2 V1.2, 2007.

[i.46] National Highway Traffic Safety Administration (NHTSA), Department of Transportation (DOT): "Notice of Proposed Rulemaking, Federal Motor Vehicle Safety Standards; V2V Communications, 49 CFR Part 571", Docket No. NHTSA-2016-0126, RIN 2127-AL55, January 2017.

[i.47] Irfan Khan and Jérôme Härri: "Can IEEE 802.11p and Wi-Fi Coexist in the 5.9GHz ITS band?", IEEE 18th International Symposium on A World of Wireless, Mobile and Multimedia Networks (WoWMoM), Macao, 2017.

[i.48] CAR 2 CAR Communication Consortium: "Coexistence investigations between ETSI ITS and RLAN in the band 5.855GHz to 5.925GHz", White Paper, 2017.

[i.49] World Radiocommunication Conference 2015 (WRC-15) Agenda.

NOTE: Available at https://www.itu.int/dms_pub/itu-r/oth/12/01/R12010000014A01PDFE.pdf.

3 Definitions, symbols and abbreviations

3.1 Definitions

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

IEEE 802.11p: amendment to the IEEE 802.11™ standard to add wireless access in vehicular environments, defining enhancements to 802.11™ (the basis of products marketed as Wi-Fi) required to support ITS applications

observation slot: period during which the operating channel is checked for the presence of ITS transmissions

RLAN devices: 5 GHz wireless access systems (WAS) including RLAN equipment

Transport and Traffic Telematic (TTT): systems in which information and communication technologies are applied in the field of transport (depending on technical restrictions for road rail, water and air), traffic management, navigation and mobility management, as well as for interfaces with other modes of transport including communication in vehicles between vehicles (e.g. vehicle-to-vehicle), and between vehicles and fixed locations (e.g. vehicle-to-infrastructure)

NOTE: In the actual regulatory discussion and documents RTTT is being replaced with TTT, see ERC Recommendation 70-03 [i.19].

3.2 Symbols

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

t1 to t10	short training symbols
T1, T2	long training symbols
GI, GI2	Guard intervals

3.3 Abbreviations

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

aCWmax	Contention Window Maximum corresponding to the underlying PHY
aCWmin	Contention Window Minimum corresponding to the underlying PHY
AIFS	Arbitration Inter-Frame Spacing
AIFSN	AIFS Number
ASECAP	Association Européenenne des Concessionnaires d'Autoroutes et d'Ouvrages à Péage European (Association of Operators of Toll Road Infrastructures)
BER	Bit Error Rate
BLL	BandLoadLimit
BSM	Basic Safety Message
BSS	Basic Service Set
CAM	Cooperative Awareness Message
CCA	Clear Channel Assessment
CCSA	Chinese Communications Standards Association
C-ITS	Cooperative ITS
CSMA/CA	Carrier Sense Multiple Access with Collision Avoidance
CWmax	Contention Window maximum
CWmin	Contention Window minimum
D&M	Detect and Mitigate
D&V	Detect and Vacate
DAM	Detect And Mitigate
DAV	Detect And Vacate
DCC	Decentralized Congestion Control
e.i.r.p.	equivalent isotropic radiated power
EDCA	Enhanced Distributed Channel Access
EETS	European Electronic Toll Service
EU	European Union
FCS	Frame Check Sequence
GMES	Global Monitoring for Environment and Security
GNSS	Global Navigation Satellite System
GSM-GPRS	Global System for Mobile telecommunications/General Packet Radio Service
HGV	Heavy Goods Vehicle
I/N	Interference-to-Noise ratio
IEEE	Institute of Electrical and Electronics Engineers
IST	Information Society Technologies
ITS	Intelligent Transport Systems
ITS-G5	Intelligent Transport Systems operating in the 5 GHz band
LAA-LTE	License-Assisted Access of LTE
LBT	Listen Before Talk
LLC	Logical Link Control
LOS	Line Of Sight
LTE	Long Term Evolution
MAC	Medium Access Control
MCL	Minimum Coupling Loss
MCS	Modulation and Coding Scheme
MLFF	Multi-Lane Free Flow
MPDU	MAC Protocol Data Unit
MSDU	Mac Service Data Unit
NLOS	Non-Line Of Sight
NS3	Network Simulator 3
OBE	On-Board Equipment
OBU	On-Board Unit
OFDM	Orthogonal Frequency Division Multiplex
PDR	Packet Detection Rate
PER	Packet Error Rate
PHY	Physical Layer
PLCP	PHY Layer Convergence Procedure
PPDU	PLCP Protocol Data Unit

PRR	Packet Reception Rate
RLAN	Radio Local Area Network
RSPP	Radio Spectrum Policy Programme
RSSI	Received Signal Strength Indicator
RSU	Road Side Unit
SNAP	Subnetwork Access Protocol
TCP	Transmission Control Protocol
TD-LTE	Time Division LTE
TPC	Transmitter Power Control
TTT	Transport and Traffic Telematics
TTT-DSRC	TTT Dedicated Short Range Communications

NOTE: As defined by The European Committee for Standardization.

TXOP	Transmit Opportunity
UDP	User Datagram Protocol
UNI-DSRC	Dedicated Short Range Communications

NOTE: As defined by Ente Nazionale Italiano di Unificazione.

V2V	Vehicle to Vehicle
V2X	Vehicle to everything
WAS	Wireless Access Systems
WINNER	Wireless World Initiative New Radio

4 Overview of services under study

4.1 Existing/Proposed RLAN

4.1.1 Overview

This clause details existing and proposed RLAN regulations and technical characteristics for the 5 GHz bands under study.

4.1.2 Existing regulations in the 5 150 MHz to 5 350 MHz and 5 470 MHz to 5 725 MHz bands

EC Decision 2005/513/EC [i.4] complemented by EC Decision 2007/90/EC [i.5] addresses the designation of the frequency bands 5 150 MHz to 5 350 MHz and 5 470 MHz to 5 725 MHz for the implementation of RLANs in EU members states and ECC/DEC/(04)08 [i.6] addresses their designation within CEPT. At worldwide level these frequency bands have been allocated to the mobile service except aeronautical mobile service on a primary basis in all three regions by World Radiocommunication Conference 2003 (WRC-03). Furthermore Resolution 229 (WRC-03) [i.7] limits the use of this allocation to RLANs. Resolution 229 (WRC-03) [i.7] also requires that RLAN need to protect other specific primary services in these frequency bands.

In the EU/CEPT the following bands were identified for use by RLANs under prescribed conditions in the both the ECC and EC Spectrum Decisions:

- **5 150 MHz to 5 350 MHz:**
    - Only indoor use, mean e.i.r.p. limited to 200 mW, and above 5 250 MHz; the use of mitigation techniques such as dynamic frequency selection (DFS) and transmitter power control (TPC).
- **5 470 MHz to 5 725 MHz:**
    - Indoor as well as outdoor use allowed, mean e.i.r.p. limited to 1 W, and use of mitigation techniques such as dynamic frequency selection (DFS) and transmitter power control (TPC).

The World Radio-communication Conference 2003 (WRC-03) agreed on a new frequency allocation on a co-primary basis to the mobile service except aeronautical mobile service for the implementation of RLANs in the bands 5 150 MHz to 5 350 MHz and 5 470 MHz to 5 725 MHz. This was subject to technical and regulatory provisions included in the radio regulations, given in Resolution 229 (WRC-03) [i.7] that makes the annex 1 of Recommendation ITU-R M.1652 [i.8] mandatory. This decision noted however that in these bands the stations in the mobile service cannot claim protection from radio-determination services. The decision includes specific provisions to protect the incumbent systems, including military and meteorological radars.

The related rules and mitigation techniques for these 5 GHz bands are detailed in ETSI EN 301 893 [i.9].

4.1.3 Proposal for additional spectrum for RLANs

A substantial share of internet traffic in Western Europe is accessed over Wi-Fi and this share is anticipated to grow to approximately 60 % of total internet traffic by 2017. In addition, Licensed Assisted Access (LAA) has been identified as a technology to use the same unlicensed spectrum.

In 2012 the European Commission announced its intention to consider the designation of additional harmonised licence-exempt spectrum for RLAN services at 5 GHz through a revision of Decision 2005/513/EC [i.4] as amended by Decision 2007/90/EC [i.5].

In addition, the RSPP requires Member States, in cooperation with the European Commission, to take all steps necessary to ensure that sufficient spectrum for coverage and capacity purposes is available for all citizens by 2020.

From a technology point of view, the IEEE Std. 802.11™-2016 [i.2] and the LAA-LTE standards [i.10], [i.11] and [i.12] can support these objectives for capacity, speed and quality, but the true potential of each will only be realized with the availability of wide spectrum channels (larger than 20 MHz for LAA-LTE or 80 MHz/160 MHz for IEEE 802.11™ [i.2]). The likely availability of such wider channels will depend on the availability of more spectrum and therefore opening a contiguous band from 5 150 MHz to 5 925 MHz for RLAN use is under study. The proposed additional spectrum would roughly double capacity and support higher speeds in contended environments involving shared use.

This is in line with the European Commission mandate to CEPT issued in 2013 and which tasks the CEPT to:

- study and identify harmonised compatibility and sharing scenarios for RLAN to operate on a shared basis in an uninterrupted band from 5 150 MHz to 5 925 MHz under the condition that: appropriate protection of EU priority applications, in particular the planned introduction of GMES (Copernicus monitoring radars) in the band 5 350 MHz to 5 450 MHz and the use of safety-related ITS applications in the frequency band 5 875 MHz to 5 905 MHz, is ensured and
- ensure that coexistence of RLAN with other current civil and/or military radio equipment to which the bands 5 350 MHz to 5 470 MHz and 5 725 MHz to 5 925 MHz and adjacent bands have already been assigned or designated is safeguarded;
- develop appropriate compatibility and sharing conditions to ensure a long-term spectrum access resource for RLAN to operate on the basis of a general authorization as an essential wireless broadband infrastructure in the internal market; and
- review and/or reconfirm the compatibility and sharing conditions developed under task 2 for the final report after WRC-15 taking utmost account of the possibility of international harmonisation.

The present document has been developed as part of the work to be done by the CEPT in response to the EC mandate.

4.1.4 Technical characteristics

The current mitigation techniques used in existing 5 GHz RLAN bands can be seen in CEPT Report 57 [i.13] and the proposed characteristics of RLANs in the band 5 725 MHz to 5 925 MHz can be seen in CEPT Report 64 [i.14] and ECC Report 244 [i.15].

4.2 Transport and Traffic Telematics (TTT)

4.2.1 Overview

This clause details existing TTT regulations and technical characteristics for the 5 GHz bands under study.

4.2.2 Road-tolling applications in the band 5 795 MHz to 5 815 MHz

For the co-ordinated introduction of Road Transport and Traffic Telematics ECC/DEC/(02)01 [i.16] has identified the frequencies for road tolling applications in the band 5 795 MHz to 5 815 MHz, however this decision has been replaced by ECC/DEC(12)04 [i.17] because of availability of applicable EU legislation (Directive 2004/52/EC [i.18]).

The frequency bands 5 795 MHz to 5 805 MHz and 5 805 MHz to 5 815 MHz are identified in ERC Recommendation 70-03 [i.19], annex 5, for road tolling. The band 5a (5 795 MHz to 5 805 MHz) is used for TTT and is identified as pan-European service frequencies for road tolling applications, whereas band 5b (5 805 MHz to 5 815 MHz), is identified as national service frequencies, according to ETSI EN 300 674-2-1 [i.20] and ETSI EN 300 674-2-2 [i.21].

Directive 2004/52/EC [i.18] lays down the conditions for the interoperability of electronic road toll stations in the European Union. The Directive requires that all new electronic toll equipment brought into service are expected to use one or more of the following technologies: satellite positioning (GNSS); mobile communications (GSM-GPRS); microwave technology (TTT-DSRC). This equipment on-board of vehicles is expected to be therefore at least be interoperable and capable of communicating with all the equipment operating in the Member States using one or more of the technologies named in this Directive. The OBUs installed in vehicles have therefore bands 5 795MHz to 5 805 MHz and 5 805 MHz to 5 815 MHz included.

It should be noted that the frequency usage for road tolling (TTT-DSRC) was identified in the early 1990s and that no compatibility studies exist for this frequency identification. Therefore, CEPT has begun conducting compatibility studies between road tolling applications using the additional sub-band 5 805 MHz to 5 815 MHz and primary services recently.

Around 28 million road tolling (TTT-DSRC) OBUs are in use today, communicating with more than 20 000 transceivers (beacons) in Europe for tolling purposes. The majority of European countries have practical implementations of road tolling equipment either as nationwide road tolling equipment or local road tolling equipment (major bridges, individual toll roads or city toll system). The majority of such installations comply with ETSI EN 300 674-2-1 [i.20] and ETSI EN 300 674-2-2 [i.21] and use all four 5 MHz wide channels up to 2 W e.i.r.p. per channel for the road side units. Some implementations only use the 5 795 MHz to 5 805 MHz range such as the French national road tolling system. The use of 8 W road side unit equipment is not as common. State of the art technology does not use higher power for multiple lane management. The Harmonised European Standards ETSI EN 300 674-2-1 [i.20] and ETSI EN 300 674-2-2 [i.21] identify the frequency range 5 795 MHz to 5 805 MHz as pan-European service frequencies and 5 805 MHz to 5 815 MHz as national service frequencies.

There are also more than 1 000 small systems implemented throughout Europe over the last 15 years to 20 years which are operated in individual buildings, pre-dominantly in parking garages, which are not strictly speaking "road tolling" systems. Other known implementations outside of pure road tolling are found at ferry operators. These applications operate under a more relaxed national regulatory regime.

Commission Implementing Regulation (EU) 2016/799 implementing Regulation (EU) No 165/2014 [i.22] lays down the requirements for the construction, testing, installation, operation and repair of tachographs and their components. Directive (EU) 2015/719 [i.23] lays down the maximum authorized dimensions in national and international traffic and the maximum authorized weights in international traffic.

Electronic road tolling systems share the same radio parameters, operate in the same 5 795 MHz to 5 815 MHz frequency band and use the same TTT-DSRC profile and verification standards as Digital Tachograph Systems.

The present document considers road tolling applications operating in the band 5 795 MHz to 5 915 MHz (also named as TTT-DSRC in Europe), Dedicated Short Range Communication (DSRC) is used differently in Europe and the United States (US):

- Europe: TTT-DSRC is used for road tolling systems in the band 5 795 MHz to 5 815 MHz. Tolling systems based on high data rate (HDR) DSRC used in Italy (specified in ETSI ES 200 674-1 [i.24] are also named HDR DSRC or UNI-DSRC. ITS refers to transport systems in the band 5 855 MHz to 5 925 MHz.
- US: DSRC refers to transport systems in the band 5 855 MHz to 5 925 MHz; road tolling in the band 5 795 MHz to 5 815 MHz is not available.

4.2.3 Technical characteristics

The technical characteristics of the road tolling systems under study and the ones used in the present document can be seen in annex 2 of ECC Report 244 [i.15].

The regulatory parameters (maximum power levels) for road-tolling systems are given in annex 5 of ERC Recommendation 70-03 [i.19].

Road tolling requirements are defined in the ETSI standards ETSI EN 300 674-2-1 [i.20] for On-Board Units (OBU) and ETSI EN 300 674-2-2 [i.21] for Road Side Units (RSU). At the time of drafting the present document these standards [i.20] and [i.21], updated to meet the Radio Equipment Directive, had not been cited in the Official Journal of the European Union.

In Italy a special version of Road Tolling TTT is used, defined in ETSI ES 200 674-1 [i.24]. Interference effects of 5 GHz RLAN on this type of TTT system have not been considered yet, and may also need to be included in future analyses.

4.3 Transport systems (ITS)

4.3.1 Overview

This clause details existing ITS regulations and technical characteristics for the 5 GHz bands under study.

4.3.2 Transport systems (ITS) in the bands 5 875 MHz to 5 905 MHz, 5 905 MHz to 5 925 MHz and 5 855 MHz to 5 875 MHz

The conditions of use of ITS in the band 5 855 MHz to 5 925 MHz have been split into three sub-bands in which different regulations and status apply:

- Traffic safety-related applications in the band 5 875 MHz to 5 905 MHz, see Commission Decision 2008/671/EC [i.25] and ECC/DEC/(08)01 [i.30];
- Possible Future extension of ITS spectrum in the band 5 905 MHz to 5 925 MHz. This band is proposed to be considered for safety-related ITS applications [i.30];
- Recommended for ITS non-safety applications in the band 5 855 MHz to 5 875 MHz, see ECC/REC/(08)01 [i.26].

The present document considers all of the above transport applications operating in the three sub-bands.

Transport Systems (ITS) are defined in Directive 2010/40/EU [i.27] as advanced applications which aim to provide innovative services relating to different modes of transport and traffic management and enable various users to be better informed and make safer, more coordinated and 'smarter' use of transport networks. ITS integrate telecommunications, electronics and information technologies with transport engineering in order to plan, design, operate, maintain and manage transport systems. Prominent examples are vehicle-to-vehicle and vehicle-to-infrastructure communication to enable applications such as collision warning, road works warning, etc.

Safety-related applications have high requirements on robustness and latency, and may need to operate in a predictable environment regarding interference and medium access. Non-safety related applications usually have lower requirements on robustness and latency. Decision 2008/671/EC [i.25] and ECC/DEC/(08)01 [i.30] harmonize 30 MHz of spectrum band for ITS applications in the 5 875 MHz to 5 905 MHz band (with a possible extension in 5 905 MHz to 5 925 MHz). This spectrum is primarily for road safety related features. ECC/DEC/(08)01 [i.30] states that "future Fixed and Mobile Service systems in this frequency band will have to prove their compatibility with ITS as well as with other existing services and applications in the band."

The general framework for the deployment of Transport Systems is set out in Directive 2010/40/EU [i.27]. The standardization mandate M/453 [i.28] on Cooperative ITS (C-ITS) led to a set of standards and specifications to be used for ITS applications.

ETSI has also prepared a new ETSI systems reference document, ETSI TR 103 083 [i.29], in support of the scheduled update of the ITS spectrum regulation in ECC/DEC/(08)01 [i.30] and ECC/REC/(08)01 [i.26]. Two main topics addressed by the ETSI systems reference document are:

- The inclusion of additional ITS station roles in the regulation in order to complement the existing role as mobile station only with infrastructure ITS stations and portable ITS stations. These ITS stations will be handled under the same ETSI harmonised standard ETSI EN 302 571 [i.31].
- Update of the spectrum mask in order to allow for technical implementation of ITS stations by taking into account the fixed 10 MHz channel bandwidth. In this context, the ECC has developed a draft ECC Report 228 [i.32] containing compatibility studies between the unwanted emissions of ITS and the following services/systems:
    - Road tolling systems between 5 795 MHz to 5 815 MHz take into account the mitigation techniques described in ETSI TS 102 792 [i.33] for the coexistence between ITS and road-tolling applications.
    - Fixed services in the band above 5 925 MHz.

3GPP Release 14 standardization work about LTE-based V2X communication, including system and radio access requirements, has been completed in March 2017. The specification of LTE-V2V using LTE sidelink is as defined in ETSI TS 136 211 [i.10], ETSI TS 136 101 [i.11] and ETSI TS 136 104 [i.12].

The Chinese Communications Standards Association (CCSA) finished the feasibility study for vehicle safety applications based on TD-LTE in 2014 and began to develop the series of industrial standard for vehicle communication based on LTE technology. Further, in March 2015, the frequency study of V2X also started in CCSA and some vehicular industrial alliances in China. The National Regulatory Authority in China is studying frequency allocation to connected vehicles.

In the US, the National Highway Traffic Safety Administration has issued a Notice of Proposed Rulemaking (NHTSA-2016-0126), [i.46] mandating vehicle-to-vehicle communications based on IEEE 802.11p and the IEEE 1609 family of standards for wireless access in vehicular environments.

Radio communication systems in the 5 GHz range can today offer communications with a high data rate, ranges up to 1 000 m, low weather-dependence, and global compatibility and interoperability for ITS communication.

The connectivity required by the ITS applications can be summarized as:

- Inter-Vehicles Communications (V2V) (this includes direct vehicle-to-vehicle communication as well as multi-hop routing involving several vehicles):
    - Linear (e.g. for convoys of vehicles);
    - Vehicle cluster covering several lanes (e.g. for lane management, overtaking assist).
- Vehicle to Roadside/Vehicle to Network (uplink) V2R/V2N and Roadside to Vehicle R2V/Network to Vehicle (downlink); or
- Vehicle to Infrastructure (V2I) and Infrastructure to Vehicle (I2V):
    - one vehicle to roadside/infrastructure equipment;
    - roadside/infrastructure equipment; to one vehicle;

- roadside/infrastructure equipment; to many vehicles (broadcast, short range and long range);
- roadside/infrastructure equipment; to selected vehicles.

- Cluster of vehicles communication, including to roadside beacon/network.

4.3.3 Technical characteristics

The technical characteristics of the ITS systems under study can be seen in annex 1 of ECC Report 244 [i.15].

5 Interference scenarios

5.1 Introduction

5.1.1 Overview

This clause sets out interference scenarios between RLAN and the various TTT and ITS services in the 5 795 MHz to 5 815 MHz and 5 855 MHz to 5 925 MHz frequency ranges.

5.1.2 RLAN and Road Tolling (TTT) - description of scenarios

The following scenarios describe realistic, worst-case scenarios applicable to both directions of interference between RLAN and road tolling.

Scenario A1: Indoor RLAN

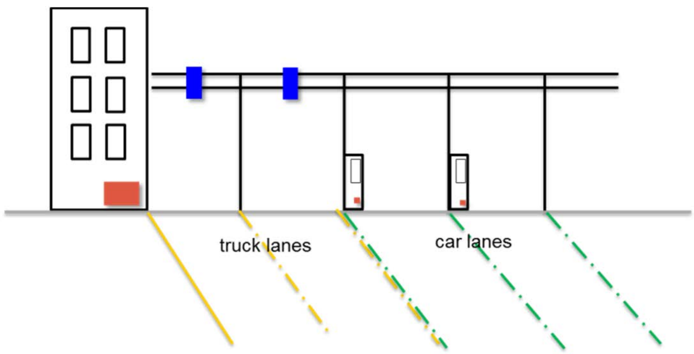


Figure 1: Scenario A1 - road tolling

The 5 GHz RLAN device is situated close to the road tolling system. Figure 1 above shows an example with multilane road toll stations. The 5 GHz RLAN transmitter appears in red and the tolling road-side units are shown in blue. In this scenario it is assumed that the 5 GHz RLAN device is close to the road tolling communication zone, but situated inside a building. Under this scenario, the minimum distance between the 5 GHz RLAN transmitter and the tolling road side receiver antenna can be around a few meters.

There are also other possible scenarios, the multilane road toll depicted here is just an example. Other examples could be tolling points within city centres, access to parking lots, etc. Buildings close to the streets not being owned or controlled by the tolling operator are considered. In this building, RLAN devices could be operated without any influence by the tolling operator.

Scenario A2: outdoor RLAN

This is the same as scenario A1 except that the RLAN device is situated outside of a building.

Scenario B: RLAN on-board a vehicle

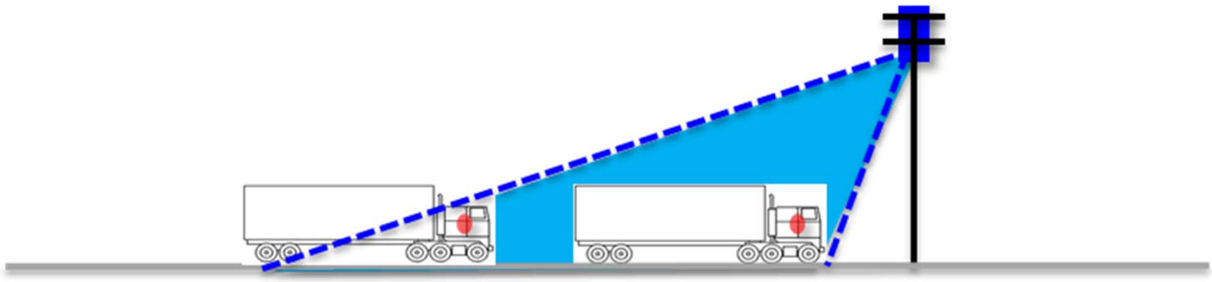


Figure 2: Scenario B - road tolling

Here the 5 GHz RLAN transmitters are found inside the vehicle. If the RLAN device is transmitting within the road tolling communication zone, its transmission would radiate through the vehicle window interfering directly with uplink communications to the tolling road side receiver antenna. In the case of a cabriolet or a motor cycle there is no wind screen, which normally attenuates the incident power level by 3 dB.

5.1.3 RLAN and ITS - description of scenarios

The following scenarios describe realistic, worst-case conditions applicable to both directions of interference between ITS and RLAN. In all cases the inter-vehicular communication is based on the ITS-G5 standard and a broad range of application from safety-related to general applications are deployed in the relevant ITS frequency bands. The presented interference scenarios are independent of the applications being deployed within the ITS frequency bands given in the following list:

- Traffic safety-related applications in the band 5 875 MHz to 5 905 MHz, see Commission Decision 2008/671/EC [i.25] and ECC/DEC/(08)01 [i.30].
- Possible Future extension of ITS spectrum in the band 5 905 MHz to 5 925 MHz. This band is proposed to be considered for safety-related ITS applications, see ECC/DEC/(08)01 [i.30].
- Recommended for ITS non-safety applications in the band 5 855 MHz to 5 875 MHz, see ECC/REC/(08)01 [i.26].

All these scenarios are mobile scenarios and thus the deployed channel models for the evaluation need to take into account dynamic multipath fading channels with different mobile speeds.

In all presented scenarios the most critical coexistence situations are the low speed, low traffic situation or the equivalent low penetration situation. In these situations, only a very limited number of ITS stations are active in a given region with a very limited number of messages (down to 1 Hz CAM rate for vehicular, significantly below that for portable devices or RSUs) sent out in a given period of time. This will decrease the detection probability of the ITS packets by a RLAN device deploying mitigation techniques. These timing constraints have to be part of any future detection parameters.

Scenario A1: Indoor RLAN

Figure 3: Scenario A1 - ITS vs indoor RLAN

The 5 GHz RLAN device is placed inside a building at street level. Under this scenario, the minimum distance between the 5 GHz RLAN antenna and the ITS antenna, placed on the roof of a vehicle, can be a few meters.

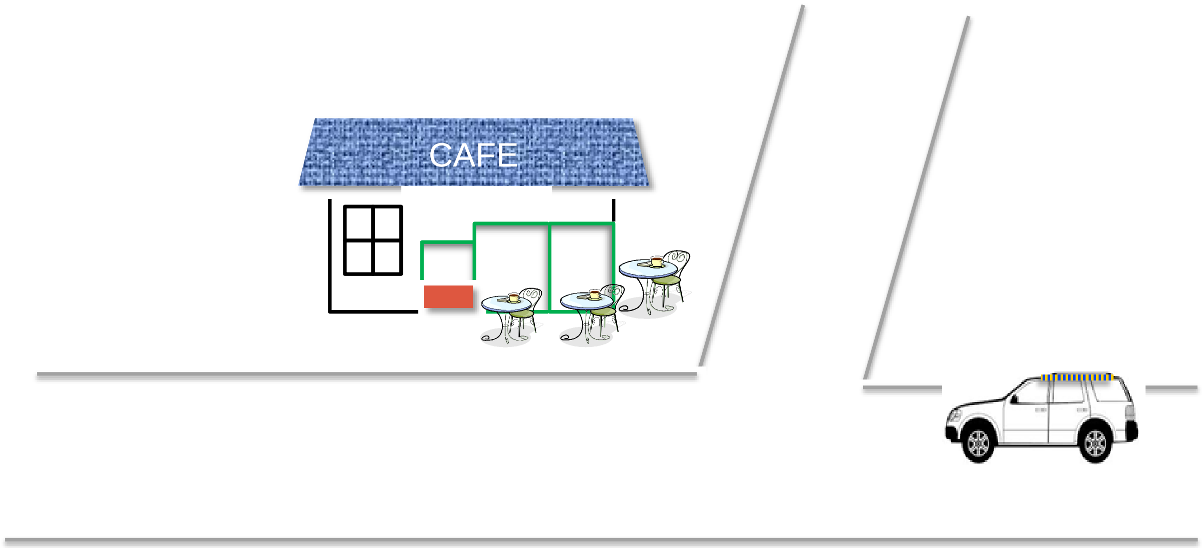


Figure 4: Scenario A1 - ITS vs indoor RLAN with low density traffic

In figure 4 a low density and low speed situation is depicted. In this case the number of ITS messages which can be used for detection will be very limited. A connected ITS peer station might be out of the receiving reach of the RLAN station (hidden node for the detection). The initial channel availability check time and the channel availability check time needs to be adapted to this kind of scenario.

Scenario A2: Outdoor RLAN

This is the same scenario as A1 but where the 5 GHz RLAN device is situated outside. Under this scenario, the minimum distance between the 5 GHz RLAN antenna and the ITS antenna placed on the roof of a vehicle can be approximately a few meters. The area to be protected here is higher than in the scenario A1 since no additional attenuation indoor to outdoor can be assumed.

Scenario B1: In-vehicle RLAN with external ITS antenna

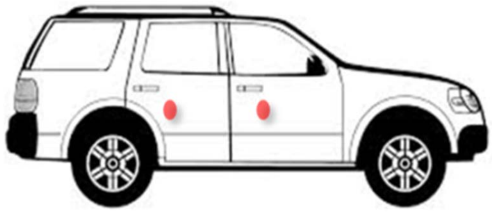


Figure 5: Scenario B1 and B2 - In-vehicle RLAN with ITS internal or external antenna

One or more 5 GHz RLAN devices are situated inside the vehicle. The ITS antenna is installed on the roof of the vehicle. There can be a distance of around 1 m between the interferer and the victim. The attenuation between the ITS antenna and the 5 GHz RLAN antenna is highly variable and is dependent upon things such as antenna positions, antenna performance, the material used for the vehicle roof (e.g. glass or metal).

In this co-location scenario the operation of RLAN in the specified ITS bands should not be possible as long as the vehicle is switched on. The detection of the ITS station will be simple due to the high receive power levels. For all RLAN systems which are fixed installed in vehicles the ITS bands and the adjacent band should be avoided.

Scenario B2: In-vehicle RLAN with in-vehicle ITS Antenna

This is the same scenario as B1 but with the ITS antenna integrated inside the vehicle passenger compartment. There can be a distance of less than 1 m between the interferer and the victim.

In this co-location scenario the operation of RLAN in the specified ITS bands should not be possible as long as the vehicle is switched on. The reliable detection of the ITS station will be simple due to the high receive power levels. For all RLAN system which are fixed installed in vehicles the ITS bands and the adjacent band should be avoided.

Scenario C: Portable ITS stations for vulnerable road users and outdoor RLAN devices

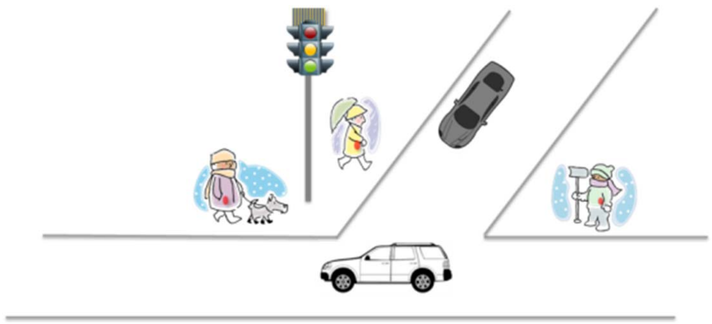


Figure 6: Scenario C: portable ITS and RLAN outdoor deployment

The ITS radio is mounted at the road side such as on a traffic light. One or several pedestrians (vulnerable road users) are equipped with portable ITS devices to be able to participate in the ITS traffic safety operations.

One or several 5 GHz RLAN devices are in close proximity. In figure 6, some of the pedestrians carrying smart devices, including RLAN and ITS, are waiting under a traffic light to cross the street. Other RLAN devices might be installed in the surrounding buildings or vehicles.

It can be assumed that the portable ITS devices have a limited Transmission (TX) power below the typical TX powers of vehicular ITS stations and the message rate will be significantly low (e.g. 0,2 Hz). In this scenario the portable devices including ITS and RLAN have to be seen as additional interference source and also as interfered devices.

5.1.4 Proposed evaluation settings

In this clause the most important settings for any performance evaluation of a coexistence mechanism will be presented. At this stage it can be assumed that these settings are the most challenging protection situation for any mitigation mechanism which has to be defined for each of the above RLAN and ITS interference scenarios.

Suggested evaluation settings are detailed below:

- Low traffic density: one ITS station in radio vicinity/visibility to RLAN devices.
- Low speed, less than 30 km/h, leading to 1 Hz CAM message rate for vehicular ITS stations needs to be assumed.
- For portable ITS devices with very low message rates and pedestrian speeds below 5 km/h.
- RSU beaconing with low message rate.
- Different Transmit Power to be assumed.
- Target performance in the sense of lost messages per time period in the ITS systems:
    - It is important to minimize the probability that two consecutive messages from the same ITS source are being interfered.
    - Detailed evaluation criteria and target performance figures have to be provided.
- High density and high speed scenarios are not as critical for detection as the low density, low speed scenario:
    - In the case of high-speed the signal reception could be challenging due to the high Doppler.
    - A single message missed could be critical for the overall system performance. In high density ITS penetration scenarios with high speed it can be assumed that the significant amount of messages will lead to a much higher detection probability and thus protection performance.
- Hidden nodes need to be taken into account in the evaluation scenario.
- In the evaluation some other parameters should be taken into account as additional mitigation factors to protect the ITS systems operating in the band 5 855 MHz to 5 925 MHz. A reduced spectral power density in the critical bands would lead to an additional mitigation factor which could be taken into account in the evaluation process.
- RLAN power density in the critical bands:
    - Here the most critical scenarios are:
        - low density; and
        - low speed traffic situation with only one message per second or significantly below for portable ITS stations or RSU.
- The mobile environment of operation of the ITS systems requires the deployment of multipath fading channel models for the evaluation of the performance. This has also to be taken into account in the future implementation of the devices itself.

A summary of the parameters that have been used in the simulation contributions of the present document is included in clause B.5.

6 Coexistence and mitigation techniques

6.1 Introduction

CEPT Report 57 [i.13] and CEPT Report 64 [i.14] highlight that there are still a number of open issues related to further studies (particularly on possible mitigation techniques). This clause details suggested mitigation techniques to help address the open coexistence issues between RLAN and TTT/ITS.

At the time of writing the present document the only ITS technology considered is ITS-G5 as defined in ETSI EN 302 663 [i.3]. Other technologies for ITS are not precluded.

In the present document the following proposed mitigation techniques are addressed on a case by case basis and it should be assumed that one or more mitigation technique may be required to achieve coexistence.

The mitigation techniques are discussed in terms of feasibility and impact on RLAN operation in the corresponding clause 7.

6.2 Mitigation techniques to enable coexistence of RLAN and road tolling (TTT)

Minimum Coupling Loss (MCL) calculations for both directions of interference between RLAN and Road Tolling have been performed in ECC Report 244 [i.15] and CEPT Report 64 [i.14]. Results of the calculations show the need for significant separation distances if compatibility is dependent upon protection to an I/N level of -6 dB. No studies have been conducted to analyse the actual effects of this I/N level being reached due to intermittent interference.

As a result, work on mitigation techniques was initiated and several approaches have been suggested to enable the coexistence between RLAN and road tolling.

Time domain effects in regard to sensing procedures (e.g. listening time, non-occupancy time) or the effect of RLAN network deployments on POD (Probability of Detection) and the associated aggregate interference environment have not yet been considered.

Background on mitigation techniques to enable coexistence of TTT and ITS

As a background for the study of coexistence of RLAN and road tolling, this clause describes the implemented mitigation technique between ITS and road tolling.

The ITS bands 5 855 MHz to 5 925 MHz are out-of-band compared with the TTT band 5 795 MHz to 5 815 MHz. Because the ITS transmitter antenna can come very close to the sensitive road toll receiver antennas (as close as 1 m) studies have shown that road toll systems will be interfered, even if the two different bands are not overlapping. To protect road toll installations against interference from ITS a mitigation technique is implemented according to ETSI TS 102 792 [i.33].

To enable a lot of users in one channel, the ITS transmitters are transmitting with a low duty cycle. Typically a message is transmitted 1 time to 10 times each second with a message length of 1 ms. One single ITS transmitter will not interfere with a road toll system, several ITS transmitter closely located to a road toll station are necessary for interference. To achieve flexible solutions, four different coexistence modes are allowed by the ITS station. The different modes are made of a combination of reduced output power and reduced duty cycle.

The most difficult part of the mitigation technique is the detection, i.e. how does the ITS station know where the road toll stations are located. There are two possible options allowed, a minimum of one of these options is mandatory:

1) One of the detection options is the road toll detector. A road toll detector is added to the ITS station, normally the same antenna is used. To avoid false alarms, triggering coexistence mode when not needed, the detected signal is expected to be a road toll signal, just a simple power detector is not enough. The road toll detector has a limited range, this reduces the error of positioning. Because the detector has limited range, shorter than the radius of the protection zone, the ITS station is expected to transmit the road toll detection in an ordinary ITS CAM message. ITS stations using road toll detectors are expected to also be alert for CAM messages with road toll information. This means that there is a risk that one single ITS station will switch to coexistence mode too late; however as described above, it is only when several transmitting ITS station are close to the road toll station that there is a risk for interference.

2) The other detection option is the protected zone database. All road toll station positions are stored locally in a memory in the ITS station. The source of this data base is downloadable using the Internet. The ITS station is equipped with a GNSS position device. When the position is close to a road toll station the coexistence mode is activated. Because of moving, temporary and new installed road toll stations, the ITS station should also be alert to road toll protection information in ordinary ITS CAM messages. These special road toll stations are equipped with their own ITS beacon, warning surrounding ITS stations to protect this road toll station. The ITS beacon should be designed in such a way that it does not interfere with the road toll station itself.

6.3 Detection of road toll stations

6.3.0 Overview

As a result of previous studies, CEPT Report 57 [i.13] and ECC Report 244 [i.15] list approaches for coexistence between TTT and RLAN. While these reports list combined approaches, here a further distinction between the detection part and the mitigation part is made. All approaches detailed in the above two reports are covered by the following categorization and descriptions.

Detection methods can be divided into the following categories:

- Detectors monitor a frequency band and report whether it is used or not. Usually, the interfering technology monitors the frequency band of the victim technology (for energy above a certain threshold or presence of a carrier signal), but it is also possible to monitor other frequencies where the frequency use is correlated with the victim technology.
- Beacons are transmitted specifically for the purpose of protecting the victim technology. This requires the interfering technology to be able to receive and react on beacons.
- Geo-location methods aim at detecting a spatial closeness between victim and interferer by the exchange of geographic information. This is usually realized by localization and look-up of stored locations from a database of fixed victim positions.

The detection methods described in the following are concrete instances of the aforementioned categories.

6.3.1 Road toll detector

A road toll detector tries to directly detect the road tolling signal via energy detection or carrier sensing on the road tolling frequencies.

6.3.2 Detection of road toll stations via ITS-G5

This detection method is based on the assumption that in the vicinity of tolling stations there are always ITS-G5 equipped vehicles, which actively use the ITS-G5 channels. If an RLAN system detects the use of ITS-G5 channels, it should activate mitigation techniques. This way, road tolling is indirectly detected via the presence of ITS-G5 equipment.

6.3.3 RLAN beacons

One beaconing possibility to signal the presence of road tolling is to generate IEEE Std. 802.11™-2016 [i.2] beacons on channel 161 (5 795 MHz to 5 815 MHz), which covers the same band as road tolling. RLAN devices should activate mitigation techniques upon reception of a beacon frame. It is unclear how the frequencies can be used for road tolling and RLAN beaconing at the same time. The duty cycle and/or the power of RLAN beaconing has to be defined in order to protect road tolling from beaconing.

6.3.4 ITS-G5 beacons (coexistence CAMs)

ITS-G5 beacons are special messages ("Coexistence CAMs") containing protected zone information and part of the coexistence techniques between ITS-G5 and road tolling outlined in clause 6.2. These messages are Cooperative Awareness Messages (CAM) containing protected zone information. Protected zones define areas around tolling stations where mitigation methods should be active. Just as any receiving ITS-G5 station, receiving RLANs should use the contained protected zone information to trigger mitigation techniques.

6.3.5 Geo-location database

A geo-location database defines protected zones where the victim technology (road toll stations) should be protected. It is expected that the geo-location database would have the capability to hold actual information on various types of road tolling stations including fixed/static, sites under construction or planned and temporary installations. Every RLAN device uses this database and checks whether it is located within a protected zone or not. As long as an RLAN device is within a protected zone, mitigation techniques should be active.

A protected zone is defined by a centre position (geographic coordinates) and a protected zone radius. The protected zone radius should be at least the required separation distance where interference is not harmful. The separation distance depends on the output power of the RLAN device and these need to be further investigated as part of future work defined in clause 7.7.3. The approach of using a geo-location database is also part of the ITS road toll coexistence described in clause 6.2. The locations of road tolling stations are relatively stable, since road construction and roads works with impact on tolling system installations and new tolling system deployments have usually long planning terms. Mobile enforcement vehicles cannot be detected via the geo-location database, therefore this method has to be complemented with a detection method for TTT on mobile enforcement vehicles.

Today it is unclear how many protected zones are needed, the number can be assumed to be less than 10 000 for the existing European road network.

6.4 Mitigation methods to reduce interference to road tolling (TTT)

6.4.0 Overview

Previous studies in CEPT Report 57 [i.13] and ECC Report 244 [i.15] suggested that for mitigation the TTT frequencies are "not available for RLAN use" upon detection, i.e. the actual mitigation part is to vacate the TTT frequencies. In the present document further mitigation methods according to the following categorization are investigated.

Mitigation methods can be divided into the following categories:

- Vacating a channel/frequency non-use.
- Change of transmit parameters:
  - Output power limitation.
  - Duty cycle limitation.
- Coordinated use of the same frequency band, i.e. interoperation on MAC layer or higher layers.

The mitigation methods described in the following clause 6.4.1 to clause 6.4.4 are concrete instances of the aforementioned categories.

6.4.1 Vacate/frequency non-use

Vacating a channel upon detection is a method to protect a victim technology by not using the frequency band in which interference is harmful. This method can be combined with a signal detector or beacon detector or with a geo-location database.

For protecting road tolling by vacating the channel, the following should be considered:

- The road tolling frequency band is vacated immediately upon detection. In order not to violate this requirement, RLAN uses a detection method before using the frequency band.

- The vacation period, i.e. duration of frequency non-use, is dependent upon the detecting method. If geographic protected zone information (such as specified for TTT/ITS coexistence, see ETSI TS 102 792 [i.33]) is available, the vacation period is at least the time an RLAN is inside a protected zone during the protected zone's validity duration. When using other detection methods, the vacation period is a multiple of the detection frequency (detector sampling period or beacon interval) or a multiple of a road tolling transaction periods (including inter-frame spacing), whatever is longer. The multiple depends on the probability of detection and the targeted reliability, e.g. if the detection probability is 0,5 then from a geometric distribution follows that 7 samples are needed to reach 99 % probability. The vacation period includes the reaction time to leave a channel and a sufficient listening period after the protected zone was left (relevant for mobile RLANs) and before the vacation period ends. The size of protected zone or the length of the vacation period needs to be further investigated as it is dependent upon the protection priority. Besides the in-band protection, the size of the necessary guard band also needs to be investigated.

6.4.2 Transmit power control

Transmit power control (TPC) describes a method of using lower transmit powers upon detection in order to reduce interference to a level that is tolerable by the victim technology. For protection of road tolling, RLAN transmit power levels are assumed to be in the order of -50 dBm e.i.r.p. dependent upon protection to an I/N level of -6 dB. This follows from the MCL calculation and other assumptions from ECC Report 244 [i.15], clause 6.1.2. For the scenario, where RLAN is the interferer and located on board a vehicle (Scenario B) it is assumed that the interferer uses -52 dBm transmit power (including the effect of TPC) and a channel of 20 MHz bandwidth. Furthermore it is assumed that the windscreen accounts for 3 dB attenuation (wall loss).The resulting -55 dBm per 20 MHz correspond to a net Tx power density of -68 dBm/MHz. The difference of this value to the allowable interfering power level at the TTT receiver of -128 dBm/MHz gives a desirable attenuation of 60 dB. 60 dB attenuation can be achieved by a separation distance of 4 m, which is a typical distance between TTT roadside equipment mounted on a gantry and a vehicle within a tolling zone. Thus a transmit power of at most -52 dBm e.i.r.p, would be required to protect TTT roadside equipment.

There has been no analysis of RLAN versus TTT sharing using the normal RLAN LBT mechanism (as part of the CSMA/CA protocol) as a mitigation technique in these situations. This should only be considered in situations where the RLAN can see TTT signals at levels above the RLAN Energy Detect threshold at RLAN power levels where harmful interference would not occur to TTT.

6.4.3 Duty cycle limitation

Duty cycle limitation describes a method of using a channel with only a limited duration per unit of time in order to leave the victim technology unaffected during the rest of the time. This is usually defined by a maximum duration of uninterrupted channel occupancy (T_{on}) and a dependent minimum idle duration (T_{off}). This method can under certain circumstances reduce the impact of interference, provided that the interfering technology leaves so much idle time to the victim technology that the major fraction of the communication is unaffected and losses due to interference do not exceed a tolerable maximum (i.e. do not cause harmful interference).

Tolling transaction times differ depending on the specific road tolling system. As an example, a tolling transaction (i.e. the message exchange sequence between road side equipment and on board equipment) has to be finalized within 70 ms according to the Austrian HGV Tolling System - EETS OBE Requirements Specification [i.34]. Within this time, only one interference event of approximately 1 ms can be tolerated, since vehicles pass through a small communication zone at high speed (e.g. 130 km/h on highways in Austria, France, Italy) and further repetitions are not possible in short time. This limitation of 1 ms tolerable interference duration within 70 ms means, that the duty cycle of the interfering technology should not exceed 1,4 %. Note that this is a collective limit for all RLAN devices within range, and not for a single device. A detailed analytical investigation to support this is included in annex A.

A more general calculation of the tolerable duty cycle than the above example for EETS OBUs can be found in the ITS/TTT coexistence standard ETSI TS 102 792 [i.33] which defines duty cycle limits agreed between ITS and tolling. ETSI TS 102 792 [i.33], clause 5.4 defines the necessary idle times (T_{off}) after an uninterrupted transmit duration (T_{on}) by the interferer.

If the T_{on} time is 1 ms, from ETSI TS 102 792 [i.33], equation 5.1 follows that the subsequent idle time (T_{off}) of the interferer is at least 50 ms (min. T_{off} limit), if there is only one interferer. The resulting duty cycle is approximately given by $T_{on}/(T_{on} + T_{off}) = 0{,}02$. The idle time grows with the number of interferers. If there are 5 interferers, each using a transmit duration of 1 ms, the T_{off} time for each interferer is at least 225 ms (by ETSI TS 102 792 [i.33], equation 5.1), which corresponds to a duty cycle of 0,4 %.

If the T_{on} time is 7 ms (maximum T_{on}), from ETSI TS 102 792 [i.33], equation 5.2 follows that the subsequent idle time (T_{off}) is at least 42 ms, if there is only one interferer. This corresponds to a duty cycle of 4,9 %.

6.4.4 Packet by packet interoperation

Packet by Packet Interoperation describes a method to divide the channel use by two technologies in the time domain, where each allocation is made on a per packet (per frame) basis. The application of this method suggests a compatible medium access control (MAC) protocol.

6.5 Mitigation techniques to enable coexistence of RLAN and ITS

6.5.0 Overview

CEPT Report 57 [i.13] and CEPT Report 64 [i.14] highlight a number of open issues related to further studies on possible mitigation techniques. This clause proposes mitigation techniques to help address the open coexistence issues between RLAN and ITS in particular with regards to Enhanced Protocol recognition and Detect and Avoid mitigation techniques as detailed in the present document.

The following mitigation techniques were proposed as part of the present document to enable coexistence of RLAN and ITS.

Considerations on mitigation techniques for the coexistence between RLAN and ITS have focused on a listen before talk spectrum access mechanism, where the potential interferer tries to detect whether a channel is busy before transmitting a data packet.

Two processes are under investigation for the detection mechanism:

- Energy Detection (ED): based on whether any energy is present above a certain threshold, regardless of the form of the signal.
- Carrier Sensing (CS): tries to match the received signal with known training (preamble) signal signatures.

CS is primarily designed to avoid interference between devices where the detector is aware of the transmitters' technology and it would require RLAN to detect technology specific signals of the ITS systems. Energy detection and carrier sensing can also be combined.

6.5.1 Energy detection

Preliminary analysis during CEPT coexistence studies included in CEPT report 57 [i.13] and CEPT Report 64 [i.14] indicated that an energy detection threshold (without any consideration of the interferer and victim signal frames) of the order of -90 dBm/10 MHz would be required for a reliable detection of ITS assuming a requirement of I/N of -6 dB.

6.5.2 Detect and mitigate proposal

The following Detect and Mitigate proposal is included within the present document.

The "Detect and Mitigate" technique proposes to use a combination of energy detection and carrier sensing, such as one of the Clear Channel Assessment (CCA) modes defined in IEEE 802.11™-2016 [i.2], clause 17.3.10.6. This mitigation technique proposes three different options for EDCA parameters (Reduced EDCA, Decreased EDCA Plan A and Decreased EDCA Plan B) to give varying levels of prioritization of medium access to the RLAN and ITS devices. The EDCA parameters for these alternatives are summarized in annex C.

Simulations for "Detect and Mitigate Proposal" are included in clauses B.2, B.3 and B.4. Simulations for an RLAN defer time of 10 s (i.e. Detect and Vacate Proposal) are also included for reference. Further clarification on the parameters used for the simulation contributions are included in clause B.5.

If an RLAN device detects the operation of an ITS-G5 device in the 5 855 MHz to 5 905 MHz band, the RLAN device mitigates the effects of its future transmissions in the band on the ITS-G5 devices by reducing the probability of accessing the medium for a period of [2 s], which in turn reduces the probability of transmitting at the same time as an ITS-G5 device. This reduced collision probability is the result of two things:

1) the RLAN device employs an ITS-G5 10 MHz preamble detector, which allows it to detect nearby ITS-G5 transmissions; and

2) within a 2 s interval after the most recent ITS-G5 preamble detection the RLAN device waits longer than usual between attempts to access the channel.

In the present document where RLAN is limited to Wi-Fi, "waits longer than usual" means that the device uses larger AIFSN, CWmin, and CWmax parameters. It is important to note that the effectiveness of 2) in mitigating interference is to a large extent, directly related to the resulting increase in inter-frame space, because ITS-G5 devices cannot detect Wi-Fi transmissions below approximately -60 dBm. An ITS-G5 device, that has a pending transmission, will transmit when a Wi-Fi device is already transmitting, if the Wi-Fi signal is below -60 dBm at the ITS-G5 location. In general the longer the inter-frame space before each Wi-Fi transmission, the lower the probability that an ITS-G5 transmission overlaps a Wi-Fi transmission.

Reduced EDCA

If the start of a valid 10 MHz ITS-G5 transmission is detected during normal Clear Channel Assessment (i.e. 1 or more ITS-G5 short training symbols is detected (within 8 µs of the start of any signal with a received energy that is above -85 dBm/10 MHz as defined for Channel Busy in annex D) on any 10 MHz channel from 5 855 MHz to 5 905 MHz which is overlapping the channel of operation of an RLAN device operating in the 5 850 MHz to 5 925 MHz band at a receive level equal to or greater than -85 dBm, then the RLAN will defer to the ITS-G5 transmission.

In addition to normal Clear Channel Assessment (CCA) to determine whether the channels are idle or busy, RLAN devices use at least four 10 MHz ITS-G5 detectors that detect 10 MHz OFDM transmissions on channels 172, 174, 176, 178 and at a higher threshold on channel 180 (for example using the channel 178 ITS-G5 detector). Together the four 10 MHz ITS-G5 detectors assert ITS-G5 channels not busy (no 10 MHz short training symbol detected) or ITS-G5 channels busy (one or more 10 MHz short training symbols and two long training symbols detected on any one of channels 172, 174, 176, 178 and 180 within 32 µs).

See figure 8 and related text in clause 6.5.3 for further details on ITS-G5 detection.

If ITS-G5 channels busy is true RLAN devices employ the EDCA mechanism described in IEEE 802.11™-2016 [i.2] using the following parameters for at least 2 s following the detection event.

Table 1: EDCA parameters

802.11 Access Category	Contention Window Minimum (CWmin)	Contention Window Maximum (CWmax)	AIFS Number (AIFSN)	TXOP Limit
Background (AC_BK)	aCWmin × 2 + 1	(aCWmax × 2) + 1	18 + (aCWmin × 2) + 1	2,528 ms
Best Effort (AC_BE)	aCWmin × 2 + 1	(aCWmax × 2) + 1	12 + (aCWmin × 2) + 1	2,528 ms
Video (AC_VI)	aCWmin	(aCWmin × 2) + 1	6 + aCWmin	3,000 ms
Voice (AC_VO)	((aCWmin + 1)/2) - 1	aCWmin	(4 + (aCWmin + 1)/2) - 1	2,080 ms

The EDCA parameters employed during any of the mitigation methods have been chosen to provide varying levels of probability of access for RLAN devices. The probability of access of an RLAN device can be significantly reduced from one mitigation to another. During the 2 s interval following a detection event, RLAN devices are restricted to a single RLAN channel of operation.

If no detection events occur for 2 s, then the RLAN device may revert to the previously configured EDCA parameters and multi-channel operation. Whenever a new ITS detection event occurs during a 2 s mitigation interval, the mitigation is extended for 2 s.

Reduced EDCA uses a random back off (Extended CCA) based upon modified EDCA parameter settings to those detailed in IEEE 802.11™-2016 [i.2], table 9-137.

Outside of the ITS detection window the IEEE 802.11™-2016 [i.2] EDCA parameter set is set to the standard Wi-Fi parameter settings.

The following Decreased EDCA alternatives would provide a lower level of probability of access for RLAN transmissions in comparison to Reduced EDCA.

Decreased EDCA Plan A

1) As with the initial Reduced EDCA proposal above RLAN devices attempt to detect the presence of ITS-G5 devices in the 5 855 MHz to 5 905 MHz band.

2) If ITS-G5 devices are detected then RLAN devices modify their EDCA parameters to use larger AIFSN, CWmin, and CWmax parameters (decreasing the probability of transmitting at the same time as an ITS-G5 device) compared to those used in Reduced EDCA, see annex C:

    - The RLAN back off rule changes such that following each channel busy event (not just the one that caused the initial change in EDCA parameters) the RLAN device uses an Extended CCA of 4,5 ms to 19 ms (i.e. a period greater than the ITS CWmax for the same access category). This continues as long as any ITS device is detected as transmitting, for every RLAN transmission for a period of at least 2 s. If an ITS packet is detected at any time T during this 2 s window, the end of the window is extended till time T + 2 s.

3) After 2 s without detecting the presence of any ITS device, an RLAN device is allowed to revert to the default EDCA parameters detailed in IEEE 802.11™-2016 [i.2], table 9-137.

This proposal does reduce probability of access for RLAN transmissions outside of the 2 s window but an Extended CCA of between approximately 4,5 ms and 19 ms does reduce probability of access to RLAN devices within the 2 s window after ITS is detected.

Decreased EDCA Plan B

For Decreased EDCA Plan B steps 1) and 2) are the same as Decreased EDCA Plan A however step 3) is different as detailed below.

After 2 s without detecting the presence of any ITS device, an RLAN device reverts to a less aggressive set of EDCA parameters compared to the default EDCA parameters detailed in IEEE 802.11™-2016 [i.2], table 9-137, see annex C.

An increased Minimum Idle time reduces the probability of access for RLAN device transmissions outside of the 2 s window. An extended CCA of between approximately 4,5 ms and 19 ms reduces the probability of access for RLAN device transmissions within the 2 s window after ITS detection.

6.5.3 Detect and vacate

The following Detect and Vacate proposal is included within the present document.

This proposal views the 5 850 MHz to 5 925 MHz ITS band as a band where every 10 s, everything is new again. If a RLAN device sleeps or fails to communicate for 10 s, it cannot assume the other stations in the BSS are still active.

The ITS and RLAN channel designations are shown in figure 7.

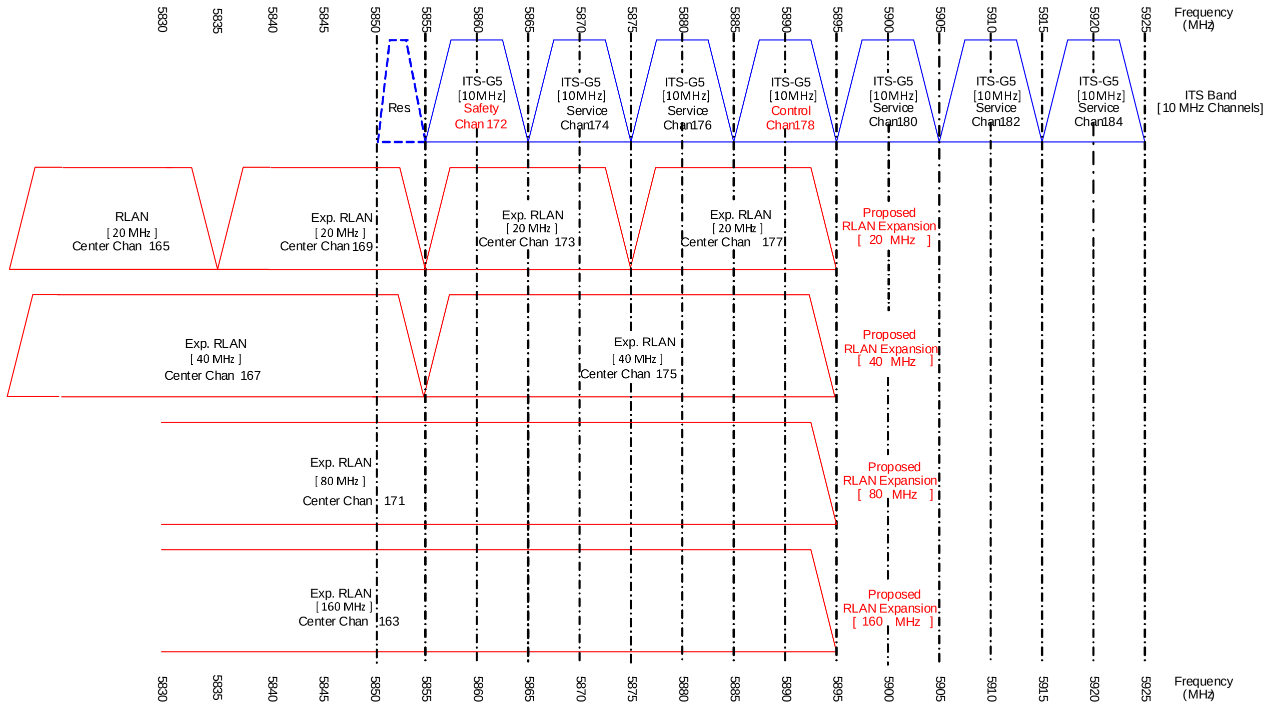


Figure 7: ITS and RLAN channelization

The 10 MHz OFDM transmissions used in ITS-G5 are specified in IEEE 802.11™-2016 [i.2], clause 17, annex D and annex E. The clause 17 short training symbols begin each valid OFDM transmission, and RLAN devices seeking to operate in the ITS band should be required to detect ITS-G5 short training symbols at [-85 dBm] in any 10 MHz channel within 5 855 MHz to 5 895 MHz and at [-65 dBm] within 5 895 MHz to 5 905 MHz.

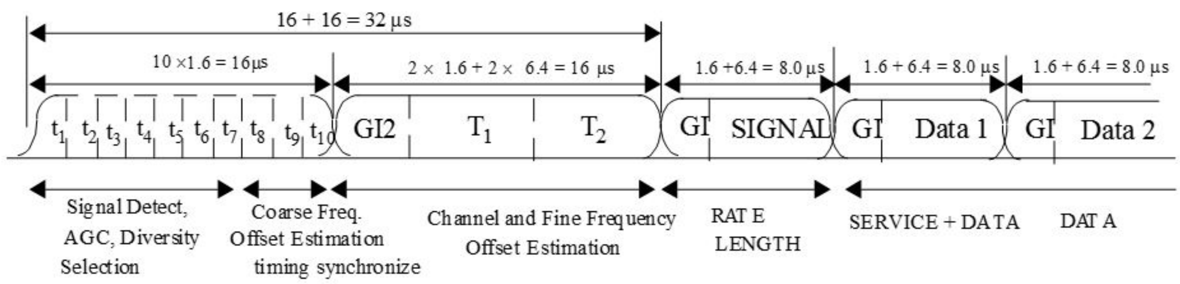


Figure 8: 10 MHz ITS-G5 preamble

Figure 8 shows the 10 MHz OFDM training structure (PLCP preamble), where t1 to t10 denote short training symbols and T1 and T2 denote long training symbols. The total training length is 32 µs. The PLCP preamble is followed by the SIGNAL field and DATA.

RLAN devices that operate in the 5 850 MHz to 5 925 MHz ITS band are capable of detection of ITS transmissions in 10 MHz channels between 5 855 MHz to 5 905 MHz.

In addition to normal Clear Channel Assessment (CCA) to determine whether the channels are idle or busy, RLAN devices use at least four 10 MHz ITS-G5 detectors that detect 10 MHz OFDM transmissions on channels 172, 174, 176, 178 and at a higher threshold on channel 180 (for example using the channel 178 ITS-G5 detector). Together the four 10 MHz ITS-G5 detectors assert ITS-G5 Channels Not Busy (no 10 MHz short training symbol detected) or ITS-G5 Channels Busy (one or more 10 MHz short training symbols and two long training symbols detected on any one of channels 172, 174, 176, 178 and 180 within 32 µs). The ITS-G5 Channels Not Busy and ITS-G5 Channels Busy states are mutually exclusive and exhaustive. The ITS-G5 Channels Busy remains true for at least [10 s] after it becomes true. The use of these four ITS-G5 detectors, referred to as ITS-G5 Clear Channel Assessment (ICCA), is independent of and in addition to normal RLAN Clear Channel Assessment.

A 30 minute history of RLAN activity above 5 850 MHz is maintained by each RLAN device. An RLAN transmit period is defined from the beginning of transmission to the time of acknowledgement, or to the completion of a retry limit when retries are attempted. An RLAN receive period is defined from the beginning of reception of the preamble to the end of reception of the frame. The sum of transmit periods and receive periods within a timeframe is the BandLoad for that timeframe. When the BandLoad since startup or the most recent thirty minutes is zero, the BandLoadLimit is 5 %, the TransmitLimit is 6 ms and the Initial TransmitLimit is 250 µs.

Both CCA and ICCA indicate channel idle and ITS-G5 Channels Not Busy before a RLAN device is allowed to transmit on channels above 5 850 MHz.

An initial transmission of [InitialTransmitLimit] is used, and if a unicast frame is not acknowledged within the retry limit, then a 10 s wait or a successful RLAN frame reception is required.

After the initial transmission, normal RLAN operation continues while ITS-G5 Channels Not Busy is true.

The simulations in clause B.3 suggest that in order to improve the likelihood that ITS transmissions are detected, an RLAN device will not transmit within 300 µs of the end of a channel busy period as determined by its normal CCA function, i.e. from the time that its CCA function detects that the channel state has transitioned from busy to idle.

All RLAN devices restrict their transmission period to [TransmitLimit] or less to minimize the probability of interference to ITS-G5 stations. Each RLAN device operated to restrict its BandLoad to be less than the BandLoadLimit for a 10 s period.

When the start of a valid ITS-G5 transmission at a receive signal level equal to or greater than -85 dBm/10 MHz is detected in 10 MHz channels of 5 855 MHz to 5 895 MHz or equal to or greater than -65 dBm/10 MHz within 5 895 MHz to 5905 MHz, then the RLAN device does not transmit in 5 825 MHz to 5 925 MHz for 10 s. Every 10 s each RLAN device evaluates its BandLoad for the most recent 10 s and adjusts its Initial TransmitLimit and BandLoadLimit.

Stated differently, if the ITS-G5 detectors detect ITS-G5 transmissions on any of the 10 MHz channels up to 5 905 MHz, then the RLAN devices vacate channels from 5 825 MHz to 5 925 MHz for 10 s.

Figure 9 shows the RLAN device state machine.

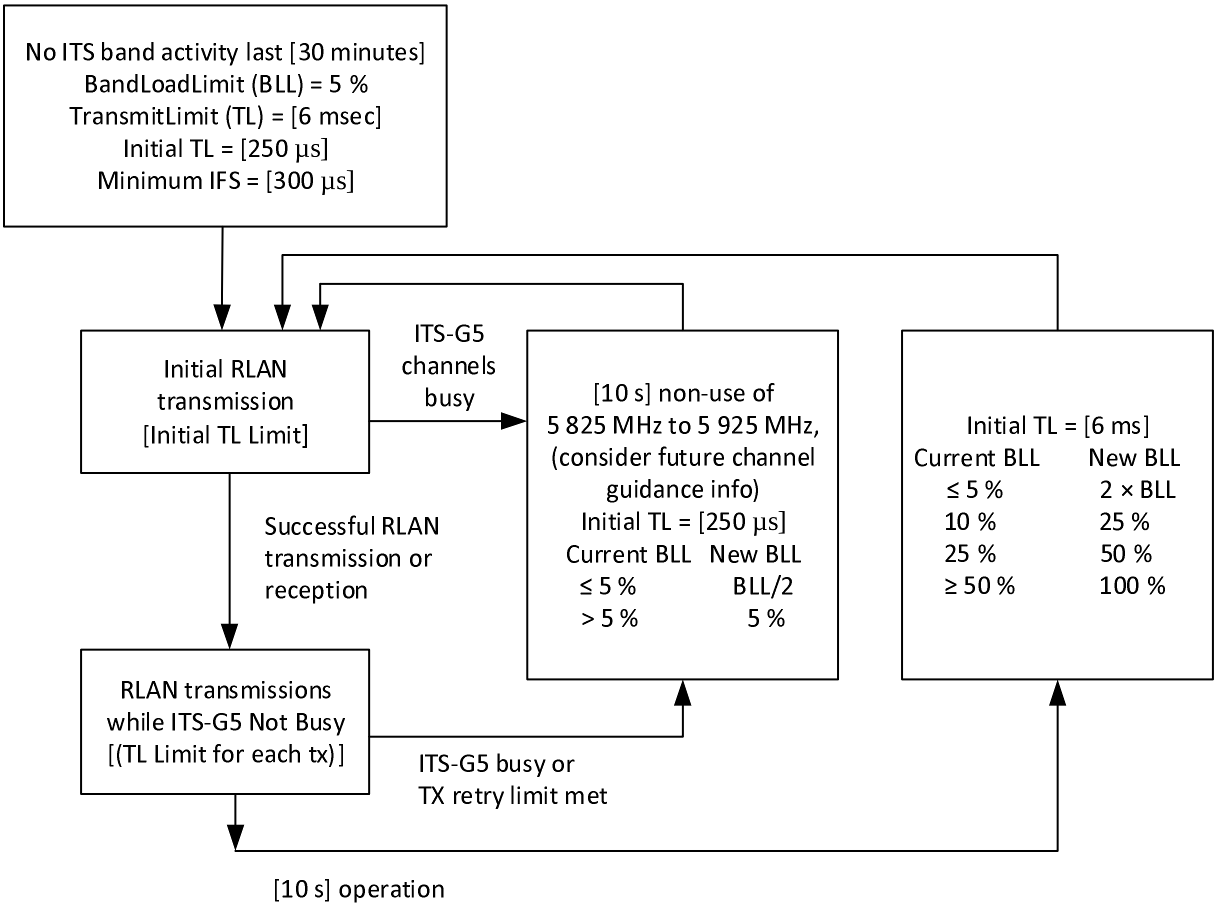


Figure 9: RLAN state machine

The channel guidance info referenced in figure 9 defines a period where the RLAN device goes silent and the conversation resumes on a channel outside of the 5 825 MHz to 5 925 MHz band within 100 ms.

The approach benefits ITS by extending protection down to 5 825 MHz (an additional 25 MHz of protection compared to today). Moreover, every RLAN device (including client devices) will be listening for ITS-G5 transmissions before using the band.

The approach benefits Wi-Fi by allowing more channels to be available for wide bandwidth transmissions where ITS devices are not present.

The regulatory requirements that would apply to this proposal are summarized in comparison table D.1.

7 Mitigation technique evaluation

7.1 Introduction

This clause focuses on evaluating the mitigation techniques highlighted in the respective parts of clause 6 of the present document. In particular the evaluations will be with regards to Enhanced Protocol recognition and Detect and Avoid mitigation techniques as detailed in the present document.

Clause 7 discusses the feasibility and impact on RLAN operation with regards to proposed mitigation techniques; however these are addressed only on a case by case basis and it should be assumed that one or more mitigation techniques may be required to achieve coexistence.

Detailed evaluation results for proposed mitigation techniques intended to enable coexistence between RLAN and ITS are reported in annex B of the present document. These results are based on three independent contributions and are found in clauses B.2, B.3, and B.4, respectively.

7.2 Mitigation techniques to enable coexistence of RLAN and road tolling (TTT)

The following detection and mitigation techniques were considered as part of the present document to enable coexistence of RLAN and Road Tolling (TTT).

7.3 Detection of road toll stations

7.3.0 Overview

The following clauses evaluate the proposed detection methods for road toll stations detailed in clause 6.3 of the present document.

7.3.1 Road toll detector

Preliminary analysis in ECC report 244 [i.15], annex 5 during coexistence studies at CEPT indicated that an energy detection threshold of the order of -100 dBm/500 kHz would be required for a reliable detection of road tolling.

Based upon feedback from the RLAN industry energy detection alone is not possible. RLAN devices measure the Signal to Interference plus Noise Ratio (SINR) only and implementations use SINR measurements to calculate Energy Detect by assuming a noise figure of -95 dBm/20 MHz. False detections occur as a level of -80 dBm is approached, based upon a 20 MHz bandwidth

7.3.2 Detection of road toll stations via ITS-G5

The effectiveness of this method depends on the correlation between road tolling locations and the presence of ITS-G5 equipped vehicles. In the vicinity of road toll stations, ITS-G5 stations transmit with reduced power and at reduced duty cycle in order to meet coexistence requirements between ITS-G5 and road tolling. The probability of detection has not been investigated prior to preparation of the present document and further work is recommended, see clause 7.7.

7.3.3 RLAN beacons

RLAN beacons in the road tolling frequency band cause in-band interference. On toll plaza installations with several independent tolling lanes, tolling transactions are scheduled independently on separate channels and overlap in time. In this scenario, it is impossible to find time slots to insert RLAN beacons of 20 MHz bandwidth, because they overlap in time and interfere with all road tolling channels.

7.3.4 ITS-G5 beacons (coexistence CAMs)

ITS-G5 Beacons are fully specified through ETSI ITS standards. Data formats are described in ETSI TS 102 637-2 [i.36] (CAM standard) and in ETSI TS 102 894-2 [i.37] (Common Data Dictionary), the usage of beacons in the ITS context is specified in ETSI TS 102 792 [i.33] (ITS/TTT coexistence standard).

ITS-G5 beacons are not suitable for broadcasting at toll plazas, where several TTT-DSRC RSUs are operated independently. In these toll plazas the TTT-DSRC transactions overlap in time and there is no fixed schedule with guaranteed idle time slots, in which ITS-G5 beacons can be broadcast. If ITS-G5 beacon transmitters are directly located at a toll plaza, they have to be operated with reduced transmit power and reduced transmit rate in order to meet coexistence requirements. A reduced transmit rate of ITS-G5 beaconing and a reduced transmit power still does not guarantee interference free operation between ITS-G5 and TTT and it lowers the probability of detection by RLAN in the vicinity of the tolling station.

This method is technology dependent and requires an IEEE 802.11™ based receiver listening to a 10 MHz ITS-G5 channel and a CAM decoder on the interferer's side.

On the victim's side, it requires transmitter installations on each tolling station. It should be noted, that for coexistence with ITS the ITS-G5 beacon transmitters are not required to be installed at the same locations as tolling stations. ITS-G5 beacon transmitters co-located with tolling stations bear the risk of interference. The protection of tolling from ITS can be achieved by placing ITS-G5 beacon transmitters hundreds of meters, even up to a few kilometers ahead of a tolling station, so that ITS-G5 equipped vehicles receive protected zone information before they reach a tolling station and are able to activate mitigation techniques in time. In such separated deployment ITS-G5 beacons are not detectable at the location of the tolling station, and thus the tolling station cannot be protected from RLANs in their vicinity.

7.3.5 Geo-location database

The use of a geo-location database is an effective method to protect long term road toll installations. At the same time it allows to re-use the frequency by RLAN outside protected zones. Protected zones will cover only a small fraction of the land area in Europe.

As an example, the Austrian tolling system can be protected by defining approximately 500 protected zones, which cover approximately 1 % of the overall land area of Austria (which is 83 879 km^2), if a separation distance of 690 m is applied (which is the required separation between TTT and indoor RLAN operating at 23 dBm/20 MHz under rural conditions according to ECC Report 244 [i.15]. Most highways are in rural areas, where not so many RLAN deployments are expected. This example of Austria is typical for a multi-lane free flow system with nationwide installation similar to other European countries such as Czech Republic and Poland.

The geo-location database in combination with frequency protection allows coexistence by spatial separation. The road tolling community is working on the corresponding database. Protected zones have to be further investigated and the role and responsibilities of stakeholders would have to be clearly defined.

Detection can be performed by a table lookup and comparison to the RLAN's own geographical location, which can be determined automatically. RLAN systems usually have Internet access that enables database updates.

The geo-location database cannot cover mobile enforcement vehicles, unless the whole road network (subject to tolling) is included in protected zones.

There is no technology lock in, i.e. the method does not depend on the interfering technology.

A geo-location database approach would be dependent upon the accurate localization of RLAN transmitters operating in the road tolling bands. Further consideration of how localization could be achieved, especially with regards indoor equipment, is required. Security measures would also need to be addressed to prevent user modification of the localization and disabling of mitigation although this security concern would be common to all mitigation techniques.

The economic availability of providing a database has been questioned but it has been noted that there may be possibilities to leverage existing databases. As an example, for the coexistence between ITS and road tolling, ASECAP will operate from 2017 a European database of protected zones which the car manufacturers use in their ITS OBUs.

7.4 Mitigation methods to reduce interference to road tolling

7.4.0 Overview

Vacate/frequency non-use, Transmit Power Control, duty cycle Limitation and Packet by Packet operation as detailed in clause 6.4 are discussed in the clauses below.

In addition the time duration of protection is a parameter for the mitigation strategy, which has to be considered in the specification of each mitigation method. Mitigation should be active for a multiple of the detection frequency, and at least until the detector gives a negative answer with high reliability.

7.4.1 Vacate/frequency non-use

Vacating a channel/frequency non-use is the most effective method for protecting the victim technology.

In the case of road tolling, only a small portion of the land area is affected by protected zones, where the road tolling frequency band should not be used by RLAN, see clause 7.3.5.

There is no technology lock in, i.e. the method does not depend on the interfering technology.

7.4.2 Transmit power control

The tolerable transmit power limit calculated in clause 6.4.2 is so low that the road tolling frequencies are actually not useable for RLAN within the vicinity of the road toll stations. It is proposed that future work should be based upon actual interference effects and measurements rather than assumed I/N (taking into account separation distances, RLAN power levels, RLAN Energy detection thresholds, etc.).

7.4.3 Duty cycle limitation

The tolerable duty cycle calculated in clause 6.4.3 is so low that the road tolling frequencies are actually not useable for RLAN within the vicinity of the road toll stations. This is further supported by the analytical investigation in annex A and related discussion below.

Interference mitigation to TTT-DSRC road tolling by duty cycle restriction is possible, as has been reported in ETSI TR 102 960 [i.43] and specified in ETSI TS 102 792 [i.33] to mitigate blocking of the TTT-DSRC OBU receivers caused by ITS-G5 transmitters. However, as has been shown in clause 6.4.3, the duty cycle limit arising from ETSI TS 102 792 [i.33] results in values below 5 %, even for a single interferer, and can go down to well below 1 % in the case of several interferers.

Since RLAN is causing in band interference to TTT-DSRC, the duty cycle limits as calculated in the present document are even stricter. In the evaluated MLFF example in clause A.4.2.1, even a single interferer should not transmit with more than 0,4 % duty cycle to avoid harmful interference to the TTT-DSRC RSU receiver.

For Toll Plazas with independent toll lanes, the interference limits are more relaxed, also because of the lower driving speed. Consequently, for open toll lanes an overall duty cycle limit of 5 % will be sufficient for most use cases (see table A.5) and for tollgates with barriers all interfering transmitters should not exceed a total duty cycle of 20 % for most use cases (see table A.6).

Based upon the above duty cycle restriction would limit the use of RLAN in vicinity of MLFF and open tollgates to very few use cases, while in the vicinity of a tollgate with a barrier around 20 % of the channel capacity could be shared with RLAN. Usually, almost all Toll Plazas have also open toll lanes and not only lanes with a barrier. Therefore, the possible duty cycle sharing scenarios are rare.

7.4.4 Packet by packet interoperation

Since road tolling and RLAN have fundamentally different and incompatible MAC layers, this method is not applicable. The same holds for interoperation on higher layers.

7.5 Mitigation techniques to enable coexistence of RLAN and ITS

7.5.0 Overview

The following mitigation techniques, as detailed in clause 6.5 were considered as part of the present document to enable coexistence of RLAN and ITS.

7.5.1 Energy detection

Based upon feedback from the RLAN industry energy detection alone is not possible where the ITS required energy detection threshold is of the order of -90 dBm/10 MHz. Levels can be detected down to approximately -75 dBm reliably however false detections occur as -80 dBm, is approached, based upon a 20 MHz bandwidth.

The following instances of ITS devices using reduced power are relevant for RLAN's using energy detection to avoid interference into ITS:

- TTT mitigation techniques integrated into the ITS system will result in varying ITS output power which should be considered for detection reliability. Here the lowest level of transmit power will be in the range of 10 dBm leading to a power spectral density of 0 dBm/MHz. This reduction of output power can happen in case of one single vehicle ITS station.

- DCC (Decentralized Congestion Control) as detailed in ETSI TS 102 687 [i.35] results in varying ITS output powers which should be considered for detection reliability. Here the lowest transmit output power from an ITS station would need to be defined and taken into account in the calculations. A realistic minimum value of transmit power could be 3 dBm leading to a power spectrum density of -7 dBm/MHz, this is recommended to be included in future work, see clause 7.7.4.

7.5.2 Summary of Detect and Mitigate and Detect and Vacate Simulations

There are simulation contributions in three separate clauses B.2, B.3 and B.4, related to evaluating the Detect and Mitigate and Detect and Vacate proposals to enable RLAN spectrum sharing within the ITS-G5 band. The results from these clauses are discussed below.

Clause B.2 discussions

Clause B.2 presents results of a simulation study involving multiple topologies with varying ITS and Wi-Fi device densities. In the smaller topologies the Wi-Fi devices are outdoors. In the larger topologies the Wi-Fi devices are either outdoors or in vehicles. ITS and Wi-Fi devices are static in each simulation. The primary metrics are ITS Packet Error Rate (PER), ITS latency, and Wi-Fi PER, all of which are measured both during the ITS detection phase and after ITS is detected.

The simulations in clause B.2.2 to clause B.2.6 support the following preliminary conclusions.

Using a calibrated channel model and PHY abstraction:

- In the steady state condition, after ITS detection, Wi-Fi has varying impact on ITS devices depending on the mitigation approach (i.e. D&V or D&M) and exact parameters of the mitigation scheme. D&V has the lowest impact, i.e. lowest PER and latency. See tables B.3, B.4 and B.6.

- In the transition period between when ITS first appears and when Wi-Fi detects the presence of ITS the choice of mitigation approach and the configuration of D&M mitigation parameters (e.g. minimum AIFS) has a noticeable impact on ITS PER. See tables B.3 and B.6:

  - D&V and D&M Decreased EDCA Plan B, both of which use an extended inter-frame space, have comparable transition period ITS PER performance, and provide better protection of ITS compared with other D&M variants.

Preliminary simulations of variations of detect and mitigate and detect and vacate proposals have shown support for the following concepts:

- D&V effectively protects ITS traffic after ITS is detected. D&M shows different levels of interference to ITS depending on the specific configuration; Decreased EDCA Plan A and Decreased EDCA Plan B use the medium less frequently than Reduced EDCA, and cause less interference.

Additional simulations detailed in clause B.2.7 support the following:

- The large topology T2 has been included in clause B.2.

- Simulations in clause B.2.7 use a NLOS channel model even between vehicles that are in fact LOS. The NLOS model produces an unrealistically short communication range for LOS ITS devices. This creates a high baseline ITS PER that could mask RLAN interference. Future simulations should adopt realistic LOS channel models where appropriate.

The simulation results have illustrated that mitigation techniques could improve the ITS performance in the presence of Wi-Fi traffic when compared to the case where no mitigation techniques are employed. Nevertheless, challenges remain especially for safety-related applications as for both scenarios 1 and 2 (conditioned upon one vehicle being only 25 m away from the intersection) the PER of ITS is still above 20 % which could not sufficiently guarantee safety-related ITS applications.

Clause B.3 discussions

Clause B.3 presents results of an analysis and simulation study. The analysis examines basic challenges for coexistence between Wi-Fi and ITS. The simulations are for two topologies in which the Wi-Fi devices are indoors. ITS and Wi-Fi devices are static in each simulation. The primary metrics are time-to-detect ITS and post-detection ITS PER.

The analysis in clause B.3 illustrates some challenges of using Detect and Vacate (D&V) and Detect and Mitigate (D&M) for sharing the ITS band. In particular:

- Clause B.3.2: Initial detection of the presence of ITS transmissions, which is required by both D&V and D&M in order to activate appropriate mitigation techniques, is largely affected by the size of the interval between consecutive RLAN transmissions. The longer the interval is, the more likely an ITS transmission will occur during the interval and will be detected by RLAN devices. Increasing the inter-frame space between RLAN transmissions improves initial detection performance.

- Clause B.3.3: After detection of the presence of ITS transmissions, D&V leaves the ITS band, and thus causes zero post-detection interference to ITS. By contrast, after initial detection D&M allows continued RLAN transmissions and does interfere with ITS. The amount of interference is a function of the quantity of post-detection RLAN transmissions.

- The simulations in clause B.3.4 support the analysis.

- Simulations of the time required for an RLAN device to initially detect ITS show that the average number of ITS transmissions needed for detection goes down significantly with a minimum RLAN inter-frame space of 300 µs.

- Simulations of the post-detection period show that RLAN transmissions under D&M cause ITS packet loss, e.g. up to 45 % ITS packet loss due to RLAN interference under D&M Decreased EDCA Plan A. By contrast, simulations of D&V using a 10 s vacate period show that since there are no RLAN transmissions after initial ITS detection, there is no ITS packet loss due to RLAN interference.

The simulation results in terms of "the average number of ITS transmissions needed before an RLAN Access Point (AP) activates vacate or mitigation mode" and "PER of ITS after the mitigation mode is activated (i.e. post-detection PER)" have clearly illustrated the differences among various spectrum sharing proposals for both the "detection" and "mitigation or vacate" phases, and thus provide valuable guidance for understanding the characteristics of these techniques.

Clause B.4 discussions

Clause B.4 presents results of a simulation study with static and moving ITS devices and static outdoor and indoor Wi-Fi devices. The indoor Wi-Fi device simulations also consider a scenario for a reduced Wi-Fi power. Two channel scenarios are included, one with fading and one without. The primary metric is ITS Packet Reception Rate (PRR).

The simulation provided in clause B.4 support the following observations:

- The DAM protection level on ITS-G5 against RLAN strongly depends on uncontrollable Wi-Fi traffic parameters (Wi-Fi Access Categories) and wireless environment (LOS, NLOS, indoor, outdoor).

- DAM Reduced EDCA does not sufficiently protect the ITS-G5 against RLAN transmissions, as it provides a systematic increase in ITS-G5 packet losses between 20 % to 50 % as a function of the distance.

- DAM Decreased EDCA Plan A provides an increased protection, as it limits the increased ITS-G5 packet loss to between 10 % and 20 %, compared to a scenario without any Wi-Fi. However, all simulation tests showed a systematic increase in ITS-G5 packet loss compared to a situation without Wi-Fi.

- The ITS-G5 protection level from DAM Decreased EDCA Plan A is Wi-Fi access category dependent and significantly degrades when Wi-Fi moves from AC_BE to AC_VO. Considering CAM/BSM sent on AC_BE, the additional ITS-G5 packet loss reaches 70 % if Wi-Fi uses AC_VO and 30 % (at distance -90 m) if Wi-Fi uses AC_VI.

- For indoor scenarios, this study illustrated high ITS-G5 additional packet loss considering DAM Reduced EDCA and DAM Decreased EDCA Plan A. The proposed reduced Wi-Fi Tx power showed to provide an increased protection to ITS-G5, but further studies should be conducted to evaluate the impact on Wi-Fi traffic. Similarly, the scenario did not consider Wi-Fi being deployed in higher building floors, but should also be considered for future studies.

7.5.3 Detect and vacate

The Detect and Vacate proposal has been evaluated as part of the simulation contributions in clauses B.2, B.3 and B.4 and included in the discussions for clause 7.5.2.

The simulations in general only take into account the 10 s non-use proposal in the 5 825 MHz to 5 925 MHz range.

In addition, the analysis of Detect and Vacate in the present document only considers the evacuation of the specific occupied channel, but not the evacuation of the complete range 5 895 MHz to 5 905 MHz (as proposed in clause 6.5.3).

7.6 Summary

Various mitigation techniques have been proposed to enable sharing with Road Tolling and Transport equipment and these were evaluated in terms of feasibility and impact on RLAN operation.

The RLAN industry proposed two possible mitigation techniques (Detect and Mitigate and Detect and Vacate) to enable RLAN spectrum sharing within the ITS band (5 855 MHz to 5 925 MHz) and various simulations were performed on these proposals. The only RLAN technology considered in the evaluations is Wi-Fi as defined under IEEE Std. 802.11™-2016 [i.2]. The only ITS technology considered is ITS-G5 as defined in ETSI EN 302 663 [i.3] are considered in the present document.

The feasibility and evaluations were addressed only on a case by case basis and it should be assumed that a combination of mitigation techniques may be required to achieve coexistence.

Based upon the results for the particular scenarios and technologies considered in the present document, conclusions on the feasibility of coexistence could not be reached. Recommendations for a continuation of these studies at CEPT are summarized in clause 7.7.

7.7 Recommendations for future work

7.7.1 Overview

The following recommendations should be considered as part of future studies at CEPT.

7.7.2 General

Time domain effects in regard to sensing procedures (e.g. listening time, non-occupancy time) or the effect of RLAN network deployments on POD (Probability of Detection) and the associated aggregate interference environment have not yet been considered and maybe consideration for further work.

7.7.3 Road tolling

- Extract from clause 6.4.1 Vacate/frequency non-use: *"The size of protected zone or the length of the vacation period needs to be further investigated as it is dependent on the protection priority. Besides the in-band protection, the size of the necessary guard band also needs to be investigated".*
- Extracts from clause 7.3.2 Detection of road toll stations via ITS-G5: *"The probability of detection has not been investigated prior to preparation of the present document and further work is recommended*".
- Extract from clause 6.3.5 Geo-location Database: *"A protected zone is defined by a centre position (geographic coordinates) and a protected zone radius. The protected zone radius should be at least the required separation distance where interference is not harmful. The separation distance depends on the output power of the RLAN device and these need to be further investigated".*
- Extracts from clause 7.3.5 Geo-location Database: The geo-location database cannot cover mobile enforcement vehicles, unless the whole road network (subject to tolling) is included in protected zones. Possible solutions need to be further investigated.

- The geo-location database in combination with frequency protection allows coexistence by spatial separation. The road tolling community is working on the corresponding database. Protected zones have to be further investigated and the role and responsibilities of stakeholders should be clearly defined.
- In addition to examining these mitigation techniques before concluding any final mitigation techniques it is recommended that testing be performed in lab conditions and out in open range conditions to investigate the real effect of RLAN interference into road tolling to determine the real separation distances based on actual interference effects. These tests will be important in both determining the actual interference effect of RLANs on Road tolling systems that already have a form of mitigation as part of its operating protocol, as well as determining suitable separation distances between the applications if necessary.
- In Italy a special version of TTT is used, defined in ETSI ES 200 674-1 [i.24]. Interference effects of 5 GHz RLAN on this type of TTT system has not been considered yet, and may also need to be included in future analyses.

7.7.4 ITS

- Compatibility considered in the present document includes Wi-Fi and ITS technology as defined in ETSI EN 302 663 [i.3]. LTE-V2X and LAA technologies as defined in ETSI TS 136 211 [i.10], ETSI TS 136 101 [i.11] and ETSI TS 136 104 [i.12] are not part of the present document and they are recommended to be considered for inclusion in future studies.
- Per discussions in clause B.3.2 further studies are needed to find an appropriate ITS preamble detection threshold for ITS detectors.
- The parameters used in simulation were varied, as detailed in clause B.5, and it is therefore recommended that for future work the parties involved agree on a set of common parameters. Future work should include agreements on at least the following prior to start of simulation work:
  - What scenarios should be simulated.
  - Channel models to use for each of the various interactions, including ITS to ITS, ITS to RLAN, RLAN to ITS, RLAN to RLAN, LOS versus NLOS, building location (e.g. floors).
  - Simulation parameters e.g.:
    - Packet sizes.
    - Transmit powers/rates.
    - Traffic flow patterns.
    - Number of runs/randomization/confidence intervals.
    - Inclusion of motion.
  - Evaluation/Protection criteria e.g.:
    - Detection time.
    - PER of multicast ITS messages.
    - Effective communication distance.
  - See also Proposed Evaluation settings in clause 5.1.4.
- It is advisable to consider both pre-detection and post-detection metrics when evaluating the impact of RLAN on ITS performance for any future work.
- Further work is proposed to consider the 'slow restart' in the Detect and Vacate protocol as defined in clause 6.5.3.

- Future work should examine the performance of the mitigation schemes under conditions where ITS-G5 packet transmission rates are reduced from the 10 Hz that is used in annex B. Proposed values were:
  - Parked or stopped vehicles send CAMs at 1 Hz.
  - Moving vehicles send CAMs at 2,5 Hz.
- DCC (Decentralized Congestion Control) is not modelled in any of the simulations included in the present document. DCC can be triggered by ITS and by interferers. It reduces ITS transmit rate and/or ITS output power, which influences detection and mitigation. It might be possible to exclude a given mitigation technique based on simulations in the report, but deciding that a sharing technique is appropriate requires additional simulations that model DCC.
- The protection criteria for safety-related and non-safety ITS has not been agreed in the present document. This is needed to conclude on the feasibility for compatibility.
- Regarding the ITS simulations in clause B.2 the PER and latency statistics presented are based on aggregation for ITS-G5 devices from 10 simulations with 10 different randomizations. Further randomizations are recommended. Also, at this time, the MCS selection algorithm choices that are built into the model are not accurately reflective of the real, sophisticated algorithms in deployed products. Those algorithms can be modified to provide an increase in the realism factor of the simulations.
- The work may also want to consider additional scenarios, for example clause B.2 includes some initial investigation into RLAN on board of a vehicle however further studies in line with other proposals in this clause is recommended.
- Clause B.2 provides some initial investigation into latency however a more detailed review should be considered as part of any future work.
- ITS-G5 employs a jitter ±5 ms in CAM generation, which is not used in the simulations of clause B.2 and clause B.4. Jitter helps prevent two vehicles from having persistent packet collisions. It could be simulated in future work.
- To verify the effectiveness of these two extensions, the inter-arrival time between a car leaving the Wi-Fi station's detection range and the next car appearing within its range should be more than 2 s and 10 s for DAM and DAV respectively. Accordingly, this would require simulation scenarios modelling bursty vehicular traffic, which are recommended for future work.
- Clause B.4.3 performed an initial investigation into the impact of Wi-Fi power reduction on ITS packet reception rate. This indicated that a reduction of Wi-Fi transmit power in the context of an indoor deployment might be necessary to mitigate interferences with ITS-G5 vehicles. The impact of such Tx power reduction on the Wi-Fi performance yet remains to be evaluated in future studies

Annex A: Duty cycle evaluations of road tolling interference

A.1 Introduction to duty cycle evaluations

Road tolling uses TTT-DSRC for Electronic Fee Collection (EFC). A TTT-DSRC tolling transaction is performed while a vehicle passes a toll gate. The tollgate can have a barrier that opens after the transaction is finished, it can also have lanes where vehicles drive slowly through without barrier. Usually these two tollgate types are combined in a so called toll plaza where up to 25 tollgates can be installed in parallel for one driving direction. The toll can also be collected at full vehicle speed in a Multilane Free Flow (MLFF) scenario, where several TTT-DSRC Road Side Units (RSU) are mounted above a motor way.

The RSU antennas have a gain of around ≥ 13 dB and are tilted towards ground. Only inside a small communication zone a toll transaction can be performed to make a match of the transaction to a vehicle possible. The communication zone has a length of around 5 m and covers the whole width of the motorway. It is located in the tolling zone rectangle shown in figure A.1, not further than 10 m away from the RSU (the exact position differs for each installation).

The toll transaction consists of downlink messages transmitted by the RSU and uplink messages from the OBU that immediately follow the corresponding downlink. When the RSU does not receive an uplink from the OBU within 480 µs after the end of the down link, the downlink is repeated. When such a retry is successfully answered with an uplink from the OBU the transaction is continued. However, such a retry consumes time, and a transaction can only be finished when the vehicles does not leave the communication zone before the transaction is over. This time constraint, given by the size of the communication zone and the vehicle speed, limits the number of retries.

Since road tolling is a payment system where an infringement is enforced and fined, high reliability requirements on the tolling technology are in place: The number of broken transactions in relation to the number of toll station passages should be less than 10^{-4}.

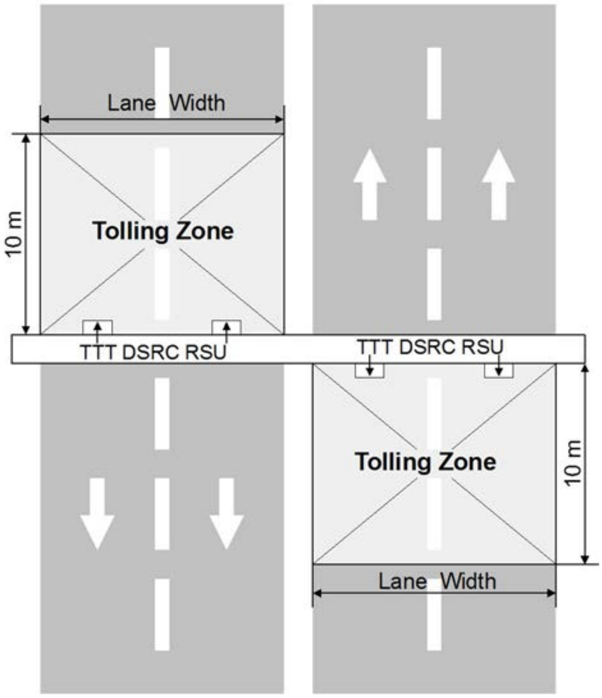


Figure A.1: Example of tolling zone geometry

Table A.1 lists the parameters, which are the basis for a mitigation method based on a duty cycle restriction.

Table A.1: TTT-DSRC parameters relevant to mitigation techniques based on duty cycle restrictions

Parameter	Value
Typical TTT-DSRC transaction duration	35 ms
Maximum TTT-DSRC transaction duration	70 ms
Typical number of downlink/uplink pairs per transaction	3
Typical average TTT-DSRC frame duration	2,5 ms
Typical retry duration	10 ms
Typical length of communication zone	5 m
Typical driving speed	5 km/h with barrier 50 km/h single lane without barrier 100 km/h MLFF (close to cities, heavy traffic) 130 km/h MLFF (rural)
Typical MLFF tolling station size	4 lanes each direction (close to cities) 3 lanes each direction (rural)

A.2 Results from previous investigations

Duty cycle based mitigation techniques to avoid interference to TTT-DSRC tolling systems have been investigated in ETSI TR 102 960 [i.43], there the focus was set on interference to the TTT-DSRC downlink. The measurements and simulations reported there show, that even for a few interferers the duty cycle of each interfering transmitter should be well below 1 %.

Concerning in band interference caused by 5,8 GHz RLAN systems, the interference either happens to the TTT-DSRC uplink, or to the uplink and the downlink. Since the length of the downlink frames is in average much shorter than the uplink frames, the results in ETSI TR 102 960 [i.43] can be seen as upper limit for the transmission rate of the interfering RLAN signal.

NOTE 1: There are two reasons why the TTT-DSRC downlink frames are much shorter, first the downlink data rate is twice as high as the uplink data rate, second the down link frames contain typically only data request messages (GET commands), while the uplink contains the requested data chunks which are longer than the requests.

NOTE 2: The longer the transmission of a victim system lasts, the higher is the probability that it overlaps with an interference signal in time and the higher is the interference probability when using a duty cycle mitigation technique (see clause A.4).

The outcome of the results from ETSI TR 102 960 [i.43] lead to the duty cycle restrictions specified in ETSI TS 102 792 [i.33]. Examples how these limits should be applied are given in clause 6.4.3 of the present document.

An example how the duty cycle limit can be calculated to avoid harmful interference to the TTT-DSRC uplink is given in clause A.4.

A.3 Evaluated scenarios

A.3.1 Typical parameters for different tollgate types

Based on table A.1 a typical MLFF example for a motorway close to a city with heavy traffic is given in table A.2.

Table A.2: Typical TTT-DSRC parameters for the MLFF tolling example evaluated in clause A.4.2.1

Parameter	Name	Value
TTT-DSRC transaction duration	T_t	35 ms
Number of downlink/uplink pairs per transaction	n_d	3
Average TTT-DSRC frame duration	T_{DSRC}	2,5 ms
Retry duration	T_r	10 ms
Length of communication zone	d_k	5 m
Driving speed	$v_{km/h}$	100 km/h
Safety distance time between the vehicles	t_s	1 s (dense traffic)
Vehicle length	l_v	5 m
MLFF tolling station size	n_l	4 lanes each direction

Based on table A.1 a typical example for an open single lane tollgate is given in table A.3.

Table A.3: Typical TTT-DSRC parameters for an open single lane tollgate evaluated in clause A.4.2.2

Parameter	Name	Value
TTT-DSRC transaction duration	T_t	35 ms
Number of downlink/uplink pairs per transaction	n_d	3
Average TTT-DSRC frame duration	T_{DSRC}	2,5 ms
Retry duration	T_r	10 ms
Length of communication zone	d_k	5 m
Driving speed	$v_{km/h}$	50 km/h

Based on table A.1 a typical example for a single lane tollgate with barrier is given in table A.4.

Table A.4: Typical TTT-DSRC parameters for a tollgate with barrier evaluated in clause A.4.2.3

Parameter	Name	Value
TTT-DSRC transaction duration	T_t	35 ms
Number of downlink/uplink pairs per transaction	n_d	3
Average TTT-DSRC frame duration	T_{DSRC}	2,5 ms
Retry duration	T_r	10 ms
Length of communication zone	d_k	5 m
Driving speed	$v_{km/h}$	5 km/h

A.3.2 Relevant RLAN parameters

For a duty cycle based mitigation technique only the RLAN message duration T_{on} and the average message rate f_i are relevant for the evaluation of the interference impact. The message duration is given by the amount of transmitted data and by the data rate. It is assumed that T_{on} is typically in the range of 1 ms to 4 ms while f_i is adjusted in such a way that harmful interference is avoided.

A.4 Duty cycle evaluations

A.4.1 Evaluation method

A.4.1.1 Interference probability as function of the duty cycle

Interference can only happen when the victim and the interferer transmit at the same time. Figure A.2 shows this case for RLAN and TTT-DSRC.

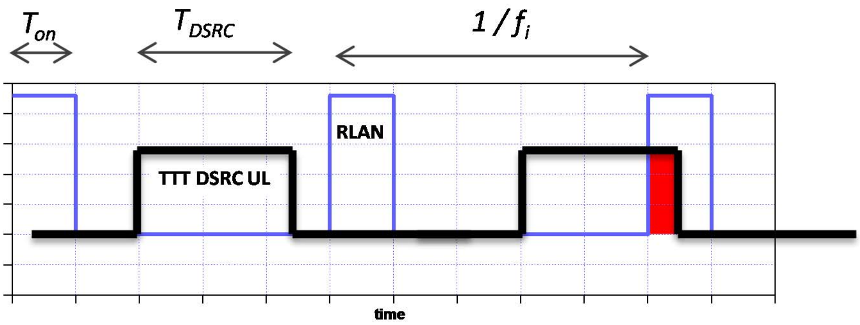


Figure A.2: Interference can happen when victim and interferer transmit at the same time

The probability p_i that an interference signal coincides with a TTT-DSRC transmission can be modelled by the conditional probability that the interference signal overlaps when a TTT-DSRC frame was transmitted. Assuming an even distributed time offset of the interfering signal compared to the TTT-DSRC frame within a range given by the reciprocal of the average interference rate f_i the interference probability is given by equation (A.1):

$$p_i = (T_{on} + T_{DSRC}) \times f_i \qquad \text{(A.1)}$$

Where T_{on} is the duration of an interfering message and it is assumed that T_{on} is shorter than the time in between two TTT-DSRC transmissions. T_{DSRC} is the duration of the interfered TTT-DSRC uplink. Hence, the duty cycle of the interfering signal D_{Ci} is given by equation (A.2):

$$D_{Ci} = T_{on} \times f_i \qquad \text{(A.2)}$$

One interference event will usually not break a toll transaction, since there is time left for the RSU to resend the request before the vehicle leaves the communication zone. When the vehicle has left the communication zone, the transaction cannot be continued and all transactions that are not finished until then are broken. Therefore, the probability that for several TTT-DSRC uplinks several retries in a row are interfered is of interest to calculate the probability of a broken transaction.

When assuming several interferers, the interference events for each TTT-DSRC retry and each downlink/uplink pair can be handled as statistically independent. From this assumption, the probability p_{b1} that a single transaction consisting of n_d downlink/uplink pairs is broken depends on the average number of maximum possible retries n_r per downlink/uplink pair.

n_r is a function of the available communication time t_c and can be calculated by subtracting the transaction duration T_t from t_c and dividing it by the retry duration T_r and the number n_d of downlink/uplink pairs as seen in equation (A.3):

$$n_r(t_c) = \frac{t_c - T_t}{T_r \times n_d} \qquad \text{(A.3)}$$

From this and with p_i from equation (A.1) the probability p_{b1} that a single transaction cannot be finished, and more than n_r consecutive retries are necessary can be calculated as seen in equation (A.4):

$$p_{b1}(n_r) = (1 - (1 - p_i)^{n_d})^{(n_r+1)} \qquad \text{(A.4)}$$

For a single lane tolling environment p_{b1} is the probability that a toll transaction cannot be finished within the available communication time $t_c = t_{c1}$. In such an installation, t_{c1} can be calculated from the length of the communication zone d_k and the driving speed v (see equations (A.5) and (A.6)):

$$v = \frac{v_{km/h} \times 1000\ m}{3600\ s} \qquad \text{(A.5)}$$

$$t_{c1} = \frac{d_k}{v} \qquad \text{(A.6)}$$

A.4.1.2 Influence of road traffic statistics

In a MLFF scenario several vehicles can pass the toll gate at the same time in parallel lanes. Even though there are several RSUs mounted in a MLFF installation, they are all synchronized and parallel toll transactions have to be handled sequentially by interleaving them. However, since it is very unlikely that several vehicles pass the toll gate with high speed at the same time, this has no relevant impact on the tolling performance. For low speeds there is enough time to handle several transactions while the vehicles pass the communication zone.

EXAMPLE 1: A typical toll transaction lasts for 35 ms. At a speed of 100 km/h a vehicle needs 180 ms to pass the communication zone of 5 m length. In this example, for an undisturbed communication, 5 lanes can be handled by the toll station simultaneously without any transaction loss.

Since the number of transaction losses caused by interference should be less than one out of 10 000 (see clause A.1) the number of simultaneous transactions in MLFF toll station cannot be neglected.

The probability p_{nT} that n_T simultaneous vehicles pass the tolling gate happen on a motorway with n_l lanes can be calculated from a binomial distribution (see equation (A.7)) under the condition that there is at least one transaction performed (see equation (A.8)):

$$p_{nT} = \frac{\binom{n_l}{n_T}\cdot\left(\frac{d_k}{d_v}\right)^{n_T}\cdot\left(1-\frac{d_k}{d_v}\right)^{n_l-n_T}}{1-\left(1-\frac{d_k}{d_v}\right)^{n_l}} \qquad \text{(A.7)}$$

$$1 \leq n_T \leq n_l \qquad \text{(A.8)}$$

Where d_k is the length of the communication zone and d_v is the distance between the vehicles plus their length l_v. The distance between the vehicles is the product of the driving speed v and the safety distance time t_s. From this d_v can be calculated (see equations (A.5) and (A.9)):

$$d_v = v \times t_s + l_v \qquad \text{(A.9)}$$

In the MLFF scenario the available communication time for each transaction $t_c = t_{cn}$ has to be shared between all transactions that are running in parallel. Equation (A.10) expresses t_{cn} as function of the number of parallel transactions n_T and the available communication time for a single transaction t_{c1} from equation (A.6):

$$t_{cn}(n_T) = \frac{t_{c1}}{n_T} \qquad \text{(A.10)}$$

Assuming that the road traffic statistic is independent from the interferer statistics, the total probability of broken transactions p_{bn} in a MLFF tolling system gets a function of the number of lanes n_l and can be derived from equations (A.7) and (A.4) (see equation (A.11)):

$$p_{bn} = \sum_{n_T=1}^{n_T=n_l} p_{b1}\left(n_r\left(t_{cn}(n_T)\right)\right)\cdot p_{nT}(n_T, n_l) \qquad \text{(A.11)}$$

A.4.2 Evaluation results

A.4.2.1 MLFF tollgate

Equation (A.11) can be used to calculate the probability of broken TTT-DSRC transactions for the TTT-DSRC parameters in table A.2. By variation of the total interferer rate f_i, the limit where the probability of broken transactions p_{bn} gets 10^{-4} can be found for different typical RLAN message durations between 1 ms and 4 ms. The result of this evaluation is shown in figure A.3.

The interferer rate for an individual RLAN transmitter can be calculated by dividing the total interferer rate f_i by the number of interfering RLAN devices, this can then be used to apply a mitigation technique based on duty cycle restriction. In the example in figure A.3, according to equation (A.2), the duty cycle of one interferer should be less than 0,4 % for a message duration of 1 ms. Hence, for two interferers each of them should not transmit with more of 0,2 % duty cycle.

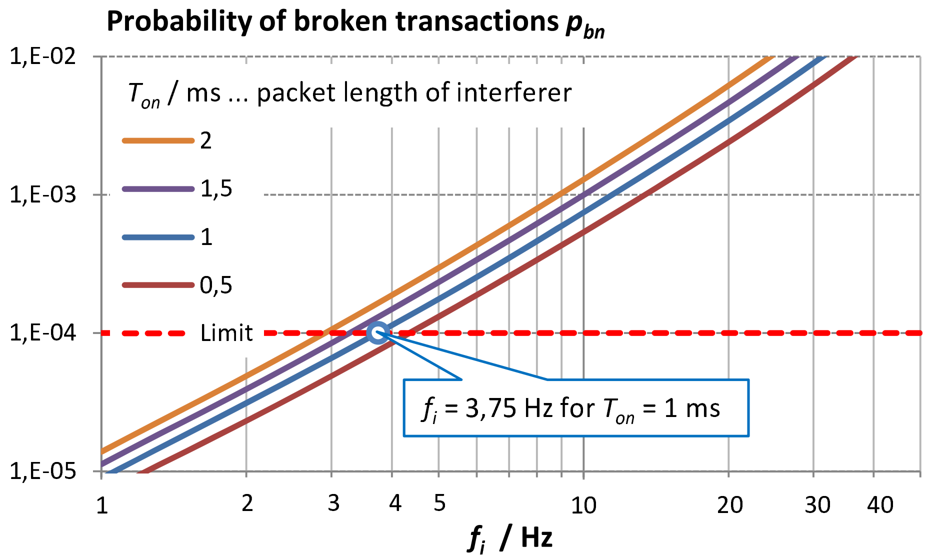


Figure A.3: Probability of broken toll transactions in a 4 lane MLFF tolling scenario for a vehicle speed of 100 km/h and different RLAN message duration as function of the total average RLAN message rate f_i

A.4.2.2 Open lane tollgate

For a single independent open toll lane without barrier the road traffic statistics are irrelevant. The number of possible retries depends only on the parameters given in table A.3. Hence, the number of broken transactions in this single lane tollgate can be calculated by use of equation (A.4).

To evaluate the upper limit for the RLAN message rate $f_{i\,limit}$ that does not cause harmful interference in this scenario, first the interference probability limit $p_{i\,limit}$ is derived from equation (A.4) by substituting the probability for broken transactions p_{b1} with the maximum acceptable probability of broken transactions $p_{b1\,limit}$:

$$p_{i\,limit} = 1 - \sqrt[n_d]{1 - \sqrt[n_r+1]{p_{b1\,limit}}} \qquad \text{(A.12)}$$

Then $p_{i\,limit}$ from equation (A.12) is substituted into equation (A.1) and the message rate $f_{i\,limit}$ is derived. The result is shown in equation (A.13):

$$f_{i\,limit} = \frac{p_{i\,limit}}{T_{on}+T_{DSRC}} \qquad \text{(A.13)}$$

Setting the probability of broken transactions to $p_{b1\,limit} = 10^{-4}$, taking the number of downlinks from table A.3 ($n_d = 3$), and calculating the maximum number of possible retries n_r from equation (A.3) with the parameters from table A.3.

$$n_r = \frac{5\,m \times \left(3{,}6\,\frac{s}{h} \times \frac{km}{m}\right) / \left(50\frac{km}{h}\right) - 0{,}035\,s}{3 \times 0{,}01\,s} = 10{,}8 \qquad \text{(A.14)}$$

results in the upper limit of:

$$p_{i\,limit} = 1 - \sqrt[3]{1 - \sqrt[11{,}8]{10^{-4}}} = 0{,}17 \qquad \text{(A.15)}$$

From the results of equations (A.14) and (A.15) the RLAN message rate limits result from equation (A.13) to the values listed in table A.5 for different RLAN message duration values T_{on}. The average TTT-DSRC frame duration T_{DSRC} was taken from table A.3 and the duty cycle limit of the interfering signal $D_{Ci\,limit}$ is calculated according to equation (A.3).

Table A.5: Message rate limits $f_{i\ limit}$ for different message durations T_{on} in an open toll lane

T_{on}/ms	$f_{i\ limit}$/Hz	$D_{Ci\ limit}$/%
0,5	56,5	2,8
1,0	48,5	4,8
1,5	42,4	6,4
2,0	37,7	7,5

A.4.2.3 Single lane tollgate with barrier

As for independent open toll lanes (see clause A.4.2.2), also for a single toll lanes with barrier the road traffic statistics are irrelevant. The number of possible retries depends only on the parameters given in table A.4. As in clause A.4.2.2 the upper limit for the RLAN message rate $f_{i\ limit}$, that does not cause harmful interference in this scenario, can be calculated by use of equations (A.12) and (A.13) and the parameters from table A.4. Where compared to the open tolling lane only the vehicle speed is lower for this scenario, which increases according to equation (A.3) the number of possible retries to:

$$n_r = \frac{5\ m \times \left(3{,}6\ \frac{s}{h} \times \frac{km}{m}\right) / \left(5\ \frac{km}{h}\right) - 0{,}035\ s}{3 \times 0{,}01\ s} = 118{,}8 \quad \text{(A.16)}$$

and raises the maximum acceptable interference probability to:

$$p_{i\ limit} = 1 - \sqrt[3]{1 - \sqrt[119{,}8]{10^{-4}}} = 0{,}58. \quad \text{(A.17)}$$

From the results of equations (A.16) and (A.17) the RLAN message rate limits results from equation (A.13) to the values listed in table A.6 for different RLAN message duration values T_{on}. The average TTT-DSRC frame duration T_{DSRC} was taken from table A.4 and the duty cycle limit of the interfering signal $D_{Ci\ limit}$ is calculated according to equation (A.2).

Table A.6: Message rate limits $f_{i\ limit}$ for different message durations T_{on} in a tollgate with barrier

T_{on}/ms	$f_{i\ limit}$/Hz	$D_{Ci\ limit}$/%
0,5	193,0	9,7
1,0	165,4	16,5
1,5	144,8	21,7
2,0	128,7	25,7

Annex B: Evaluations of the proposed ITS protection mechanisms

B.1 Introduction to ITS evaluations

This annex reports detailed evaluation results for two proposed mitigation techniques intended to enable coexistence between RLAN and ITS: Detect and Mitigate (see clause 6.5.2) and Detect and Vacate (see clause 6.5.3). The results are presented in three clauses B.2, B.3 and B.4, each of which is an independent contribution. All three evaluations focus on the important ITS intersection use case. Clause B.5 details the simulation parameters used in these evaluations and a summary of the studies is included below:

- Clause B.2 presents results of a simulation study involving multiple topologies with varying ITS and Wi-Fi device densities. In the smaller topologies the Wi-Fi devices are outdoors. In the larger topologies the Wi-Fi devices are either outdoors or in vehicles. ITS and Wi-Fi devices are static in each simulation. The primary metrics are ITS Packet Error Rate (PER), ITS latency, and Wi-Fi PER, all of which are measured both during the ITS detection phase and after ITS is detected. This annex is based on contribution BRAN(16)000078r2 [i.40].
- Clause B.3 presents results of an analysis and simulation study. The analysis examines basic challenges for coexistence between Wi-Fi and ITS. The simulations are for two topologies in which the Wi-Fi devices are indoors. ITS and Wi-Fi devices are static in each simulation. The primary metrics are time-to-detect ITS and post-detection ITS PER. This annex is based on contributions BRAN(16)000081r3 and BRAN(16)000165 [i.41].
- Clause B.4 presents results of a simulation study with static and moving ITS devices and static outdoor and indoor Wi-Fi devices. The indoor Wi-Fi device simulations also consider a scenario for a reduced Wi-Fi power. Two channel scenarios are included, one with fading and one without, The primary metric is ITS Packet Reception Rate (PRR). This annex is based on contribution BRAN(16)000138r4 [i.42].

B.2 ITS/RLAN performance analysis for a single intersection with varying topologies/device densities

B.2.1 Introduction

The following clauses provide simulation results for the proposed mitigation methods. These mitigation methods are Reduced EDCA, Decreased EDCA Plan A, Decreased EDCA Plan B and a Detect and Vacate mechanism as described in clause 6.5.3. Comparisons are made to the unmitigated case.

B.2.2 Simulation scenarios

This clause describes the simulation scenarios that are used to evaluate the proposed mitigation methods. As far as vehicle safety is concerned, intersection collision avoidance is regarded as a critical application of ITS. So in the present document, an intersection collision avoidance scenario is investigated.

It is assumed that more than one vehicle is approaching an intersection where there are obstacles, e.g. building walls, that block the drivers' lines of sight from vehicle to vehicle. The exchanged ITS message for collision avoidance is also at least partially blocked and attenuated by obstacles. The performance of the ITS communication system under such a scenario is investigated by simulation. Mobility is not assumed in the simulation for the vehicles. Instead, simulation results of multiple instantaneous simulations with randomly chosen locations are averaged over multiple traffic flow randomizations to show the general behaviour at different distances.

The traffic model used for ITS devices in the simulation is intended to emulate ITS BSM, @ 10 Hz where each BSM message has 268 octets of MAC payload. An LLC SNAP header of 8 bytes and MAC MPDU header and FCS are added to produce a PPDU on the air that has 304 bytes of PHY payload plus an additional 2 bytes of service field which is a standard part of an 802.11 formatted PPDU. Note that the 2 bytes of service field are not included in the MAC FCS calculation, but are accounted for in transmission duration.

Within a single simulation run, ITS BSM traffic is alternately enabled and disabled and Wi-Fi device traffic is constant. By successively enabling and disabling the ITS BSM traffic, three different regimes of behaviour can be observed. The first regime is steady state Wi-Fi operation without ITS traffic present, to establish a baseline of Wi-Fi performance where Wi-Fi has exclusive use of the channel. The second regime, called the transition time period begins with the first ITS transmission and ends when all Wi-Fi devices have detected the presence of ITS and entered mitigation mode. The third regime, called the mitigation period, is the steady state cooperative state reached after all Wi-Fi devices in the simulation have detected the presence of ITS devices on the channel and have invoked mitigation and which ends at the last ITS transmission in the burst. The sequence of these three different regimes repeats through a single simulation and data is collected during each regime and reported in aggregate for each regime and then summed with data from additional runs with randomized placements of Wi-Fi devices and randomized start times of traffic flows.

Wi-Fi devices are always simulated operating on 20 MHz channels with a fixed PHY layer rate of 19,5 Mbit/s.

ITS devices are simulated with either 10 MHz channelization at 4,5 Mbit/s. Where a 10 MHz channel is simulated, the channel is positioned in either the lower or upper half of the 20 MHz Wi-Fi channel, i.e. not in the centre of the 20 MHz channel.

Transmit power for both ITS and Wi-Fi devices is 18 dBm.

Figure B.1 depicts scenario 1. Parameters X and Y are the distances of each of two vehicles from the corner of an intersection. One of the vehicles is positioned at various distances (X) from the intersection and the other remains statically positioned (Y). The value of X is modified for each run of the simulation. Both vehicles are equipped with ITS devices. There is one Wi-Fi BSS positioned at the intersection. The Wi-Fi AP is located outside of the building. The Wi-Fi client devices are randomly placed, at locations which are outside of the building. Each BSS has one AP and one client device.

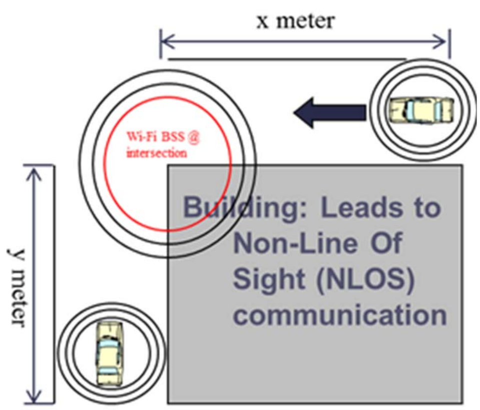


Figure B.1: Intersection collision avoidance (scenario 1)

Figure B.2 depicts scenario 2. Parameters X and Y are the distances separating one of the two vehicles from the corner of the intersection and one of two Wi-Fi BSSs (the AP of the BSS). One of the vehicles is positioned at various distances (X) from the intersection and the other remains statically positioned (Y). The position of the vehicle at the top of the diagram remains unchanged through all variants of this scenario. The position of the vehicle on the left is varied and the results for each distance variation are separately presented. Both vehicles are equipped with ITS devices. Again, all Wi-Fi devices are located outside of the building.

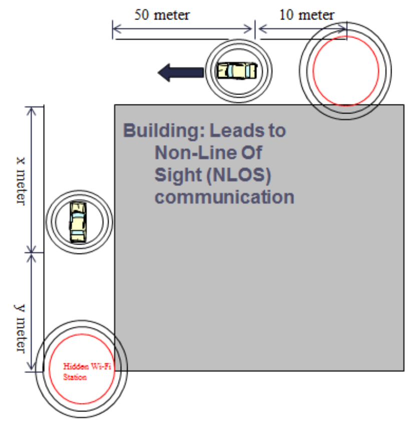


Figure B.2: Intersection collision avoidance (scenario 2)

B.2.3 Physical layer abstractions

Two physical layer (PHY) abstraction models are used in the performance evaluation of the proposed mitigation method.

The first PHY abstraction uses standard Bit Error (BER) curves under IEEE 802.11™ channel model D (11N_D). This channel model and others were developed by the IEEE 802.11™ working group based on various measurements made by several committee participants. Channel model D was created from data collected in large open spaces (indoor and outdoor) with a measured average of 140 ns rms delay spread. The path loss is modelled with the equations (B.1) and (B.2):

$$L(d) = L_{FS}(d) \qquad d <= d_{BP} \tag{B.1}$$

$$L(d) = L_{FS}(d_{BP}) + 35 \log_{10}(d/d_{BP}) \qquad d > d_{BP} \tag{B.2}$$

where *d* is the transmit-receive separation distance in m. The path loss model parameters are summarized in table B.1. In table B.1, the standard deviations of log-normal (Gaussian in dB) shadow fading are also included. The values were found to be in the 3 dB to 14 dB range.

Table B.1: Path loss and standard deviation parameters for IEEE 802.11™ channel model D

New Model	d_{BP} (m)	Slope before d_{BP}	Slope after d_{BP}	Shadow fading std. dev. (dB) before d_{BP} (LOS)	Shadow fading std. dev. (dB) after d_{BP} (NLOS)
D	10	2	3,5	3	5

The zero-mean Gaussian probability distribution is given by:

$$p(x) = \frac{1}{\sqrt{2\pi}\sigma} \exp\left(-\frac{x^2}{2\sigma^2}\right) \tag{B.3}$$

The frequency selective fading for IEEE 802.11™ Channel Model D is modelled using the cluster model as defined in the document: TGn Channel Models, IEEE P802.11™ Wireless LANs Std. IEEE 802.11™-03/940r4 [i.38].

Figure B.3 shows the Model D delay profile with clusters outlined by exponential decay (straight line on a log-scale).

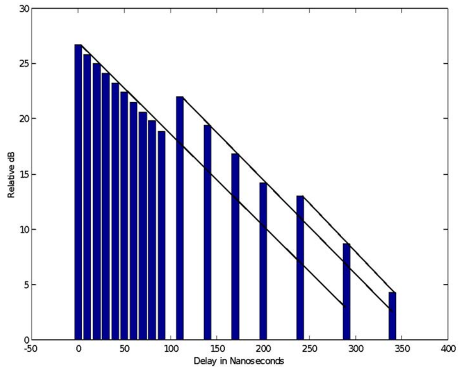


Figure B.3: Model D delay profile with cluster extension (overlapping clusters)

The second PHY abstraction model begins with channel model D parameters, but shifts the SNR-BER curves and adjusts other parameters to produce an approximate match of PER vs distance to measured results as shown in figure B.4. This model is labelled ITS_11N_D_T. Figure B.5 shows the result of the adjustments made to produce channel model ITS_11N_D_T. There is general agreement that ITS_11N_D_T is a NLOS model.

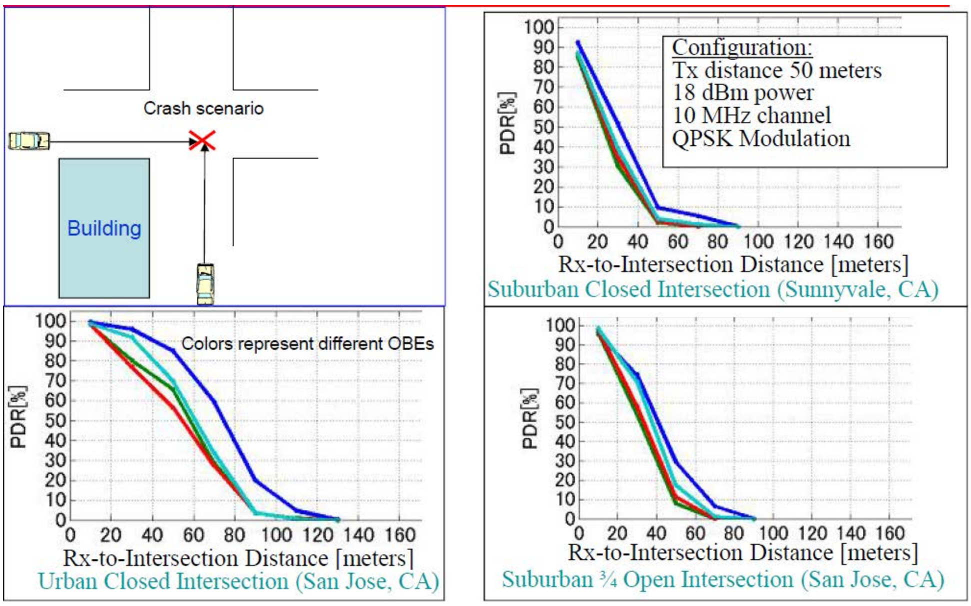


Figure B.4: Measurement results

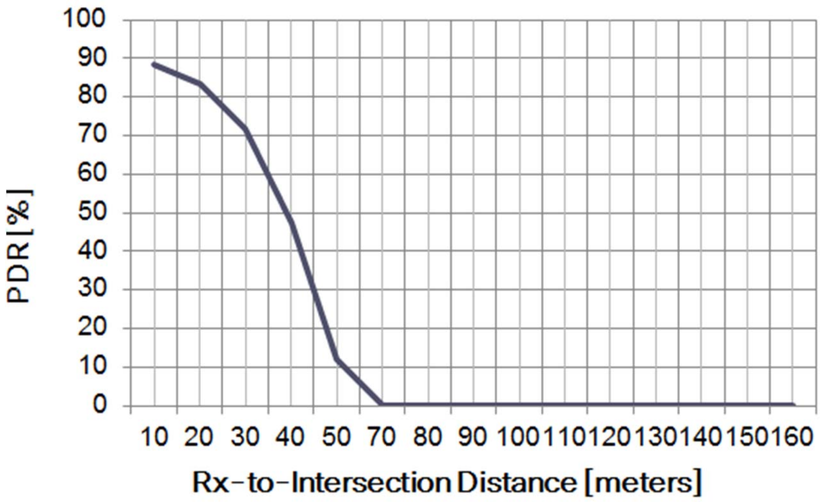


Figure B.5: PDR with Calibrated Model and PHY Abstraction

In the simulation, the path loss models are used as shown in table B.2.

Table B.2: Path loss model use within simulations

Receiver	Transmitter	Model
ITS	ITS	ITS_11N_D_T
ITS	Wi-Fi	11N_D
Wi-Fi	ITS	11N_D
Wi-Fi	Wi-Fi	11N_D

The ITS_11N_D_T model is used between the transmissions of ITS devices. The original 11N_D model is used between transmissions between Wi-Fi devices and between ITS and Wi-Fi devices.

B.2.4 Examples of transition period behaviour

As noted earlier, ITS transmissions are successively enabled and disabled in order to provide multiple instances of Wi-Fi detection of ITS devices within a single simulation run. The duration of a burst of ITS traffic is 0,9 s with an idle period of 0,6 s. The Wi-Fi ITS timeout is set to 0,25 s, so periods of exclusive use of the channel by Wi-Fi last for approximately 0,35 s with some variation in that value which is due to phase differences in the ITS transmissions. Periods of transition start with an initial ITS transmission and last until all Wi-Fi devices in the simulation have detected the presence of at least one ITS transmission. It can be seen in the results below that the period of operation where ITS devices are transmitting and all Wi-Fi devices are operating in mitigation mode lasts for approximately 0,8 s. The duration of each regime of behaviour will vary depending on the simulation conditions.

The interaction of Wi-Fi devices and ITS devices in the transition period is critical to understanding the effectiveness of a protection mechanism for ITS devices, especially if ITS devices are frequently entering and exiting an area where Wi-Fi devices are located such that the Wi-Fi devices frequently enable and disable mitigation.

Figure B.6 shows an example of the simulator behaviour for scenario 1 using a waveform viewing tool.

The first two horizontal waveform traces from the top represent the transmissions of the two ITS devices and the next two horizontal waveform traces represent the transmissions of the Wi-Fi devices. The signals represented are binary, where a value of 1 represents an active transmitter and a value of 0 represents an inactive transmitter. Red transmissions are those that end in failure, either due to high BER due to path loss or due to collision with another transmission. Green transmissions ended in successful reception by the intended recipient. BSM messages are all sent as broadcast messages and are always indicated as green/successful, even though they might have failed. This is because when more than one recipient is present, the reception status of a multicast or broadcast message might be somewhere in between 100 % received and 0 % received.

The simulation run depicted in the waveform is one in which the Wi-Fi devices are using detect and vacate. This behaviour can be seen in the waveform as the cessation of all Wi-Fi transmissions sometime after the start of a burst of ITS transmissions. In three of the instances observable in figure B.6, the detection appears to occur quickly, but in the second instance shown, there is an overlap between the ITS transmissions and the continuation of Wi-Fi transmissions which occurs because the initial ITS transmissions in the second burst are not detected by Wi-Fi.

For data collection and reporting, the transition time varies for each of these ITS transmission starts. The transition time is measured as the window of time starting from the first ITS transmission of each burst until all Wi-Fi devices have detected the presence of ITS devices and have invoked mitigation or vacate behaviour.

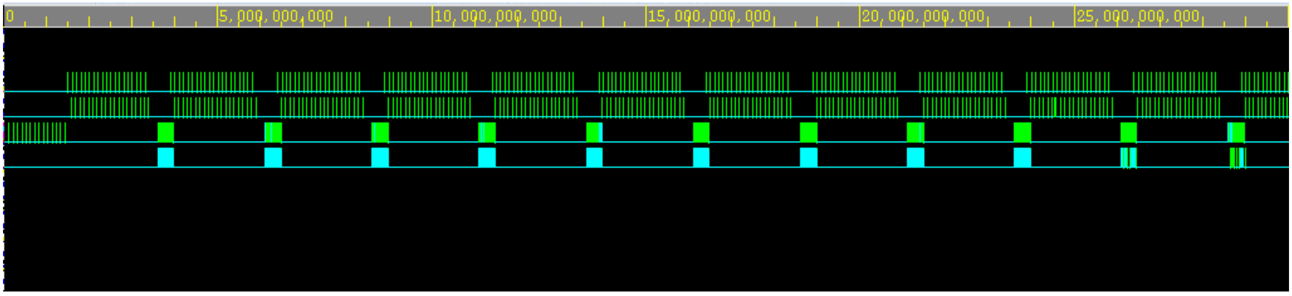


Figure B.6: Snap shot of simulation showing alternating periods of ITS transmissions with Wi-Fi devices employing detect and vacate

When the Reduced EDCA mechanism is used, Wi-Fi devices operate with a mitigated set of EDCA parameters when an ITS transmission is detected and revert back to normal EDCA parameters after the mitigation period expires. Figure B.7 shows a snapshot of simulation activity when Wi-Fi devices are employing Reduced EDCA.

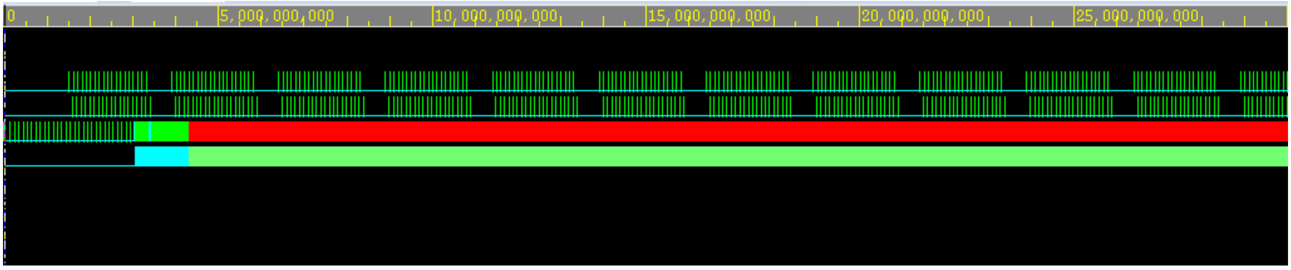


Figure B.7: Snap shot of simulation showing alternating periods of ITS transmissions with Wi-Fi devices employing Reduced EDCA Mitigation method

Figure B.8 shows a snapshot of simulation activity when Wi-Fi devices are employing Decreased EDCA Plan A. Wi-Fi transmissions are spaced closer together during the period when mitigation has turned off following the cessation of ITS transmissions versus when mitigation is on. Following some delay after the next period of ITS transmissions begins, the Wi-Fi transmissions are spaced farther apart as ITS detection has caused the Wi-Fi devices to invoke mitigation.

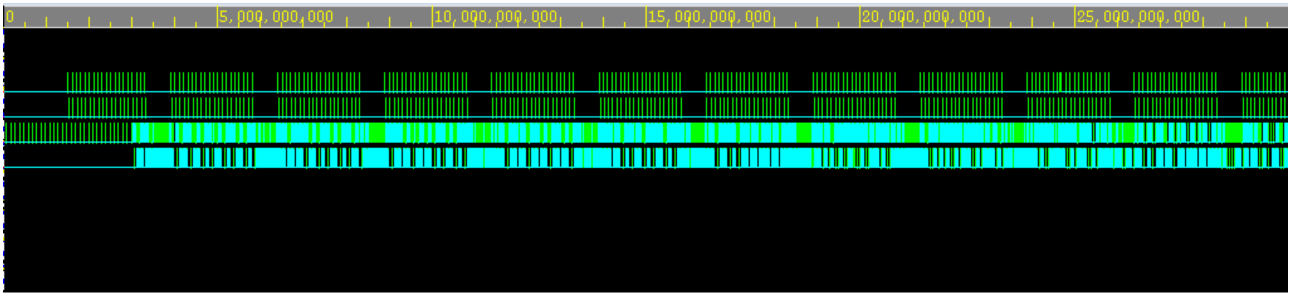


Figure B.8: Snap shot of Decreased EDCA Plan A mechanism during the transition period

Figure B.9 shows a snapshot of simulation activity when Wi-Fi devices are employing Decreased EDCA Plan B. Differences in mitigate and non-mitigate behaviour are more difficult to discern for the case of mitigation with Decreased EDCA Plan B parameters.

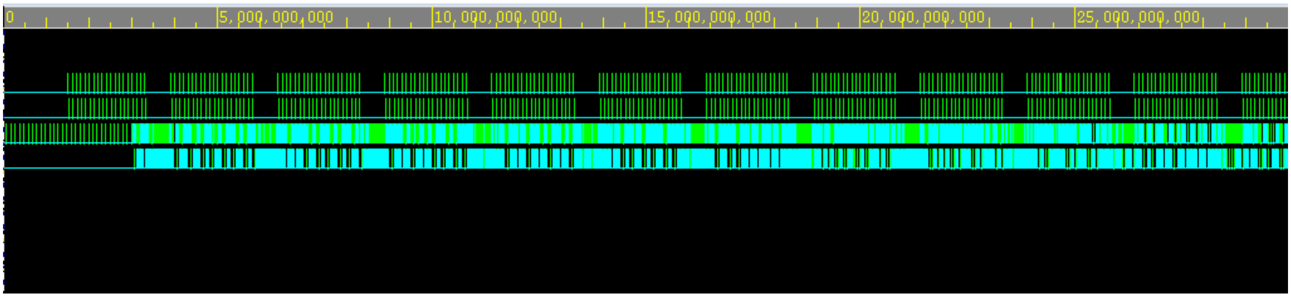


Figure B.9: Snap shot of simulation showing alternating periods of ITS transmissions with Wi-Fi devices employing Decreased EDCA Plan B method

Figure B.10 shows a snapshot comparison of ITS detection performance between Detect and Vacate and Decreased EDCA Plan B. It shows under the same simulation scenario it takes 0,6 s (3 ITS packets transmitted) for the Detect and Vacate mechanism (upper plot) to detect the ITS transmission while Decreased EDCA Plan B (lower plot) detects the first ITS transmission.

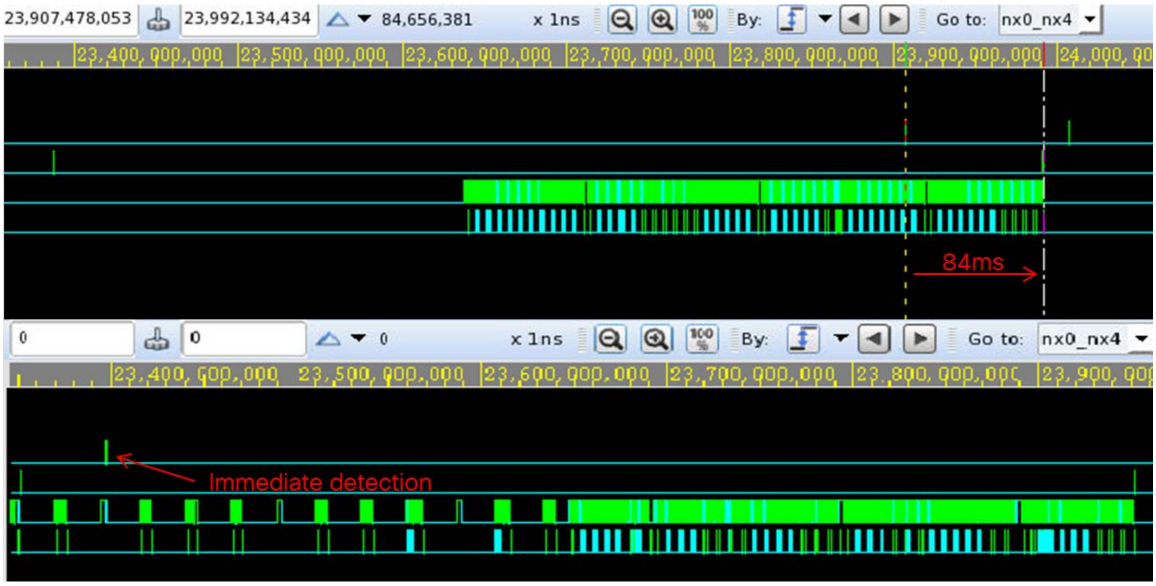


Figure B.10: Snap shot of simulation comparing detection time of Detect and Vacate and Decreased EDCA Plan B

B.2.5 Summarized simulation results

Under intersection collision avoidance simulation scenario 1, the first vehicle is 50 m (Y in figure B.1) away from the intersection, and there is a Wi-Fi BSS located at the intersection. X is the distance between the second vehicle and the intersection. In the simulations, the value of X is varied from 5 m to 45 m. For each value of X, 5 simulations are conducted with different random seeds. Each simulation includes approximately 17 on/off transitions. The results from each set of simulations with a common value of X are averaged and displayed in tables B.3 to B.5. There are approximately 85 transition periods and 85 static operation periods represented within each table. For each simulation set there are three tables. Table B.3 shows the ITS transmission PER performance and table B.4 shows the Wi-Fi transmission PER performance. Table B.5 shows latency performance for ITS transmissions. Note that ITS transmissions that were not received are counted as PER failures and are not included in the latency statistics. Wi-Fi latency values are for layer 4 source to layer 4 sink paths and therefore include the effect of any retransmissions.

The results for all simulations presented in clause B.2 were performed using UDP traffic with the exception of the additional scenarios in clause B.2.7 which were performed using TCP, see table B.19 for further details.

Note that latency values greater than 100 ms for ITS transmissions are considered as a PER failure.

Table B.3: ITS PER performance under intersection collision avoidance scenario 1

ITS device	X = 15 meters		X = 25 meters		X = 35 meters		X = 45 meters	
	Transition	Mitigation	Transition	Mitigation	Transition	Mitigation	Transition	Mitigation
Mitigation OFF	60,22 %	NA	99,15 %	NA	99,72 %	NA	99,72 %	NA
Reduced EDCA	54,38 %	53,01 %	98,94 %	92,73 %	99,54 %	95,31 %	99,66 %	96,56 %
Decreased EDCA A	55,26 %	26,89 %	98,41 %	45,40 %	99,14 %	55,07 %	99,22 %	81,82 %
Decreased EDCA B	44,42 %	26,98 %	91,34 %	43,97 %	94,08 %	57,14 %	97,32 %	81,13 %
Detect and vacate	44,16 %	13,53 %	95,00 %	22,22 %	95,94 %	38,08 %	98,01 %	72,03 %

Table B.4: Wi-Fi PER performance under intersection collision avoidance scenario 1

Wi-Fi device UDP traffic	X = 15 meters		X = 25 meters		X = 35 meters		X = 45 meters	
	Transition	Mitigation	Transition	Mitigation	Transition	Mitigation	Transition	Mitigation
Mitigation OFF	0,00 %	NA	0,00 %	NA	0,01 %	NA	0,01 %	NA
Reduced EDCA	0,00 %	0,01 %	0,00 %	0,02 %	0,00 %	0,02 %	0,00 %	0,02 %
Decreased EDCA A	0,00 %	0,11 %	0,00 %	0,03 %	0,00 %	0,01 %	0,00 %	0,01 %
Decreased EDCA B	0,00 %	0,15 %	0,00 %	0,06 %	0,00 %	0,04 %	0,00 %	0,04 %
Detect and vacate	0,00 %	NA	0,00 %	NA	0,00 %	NA	0,00 %	NA

Table B.5: ITS latency performance under intersection collision avoidance scenario 1

ITS device	X = 15 meters		X = 25 meters		X = 35 meters		X = 45 meters	
	Transition	Mitigation	Transition	Mitigation	Transition	Mitigation	Transition	Mitigation
Mitigation OFF	3,05 ms	NA	0,03 ms	NA	0,03 ms	NA	0,03 ms	NA
Reduced EDCA	2,27 ms	1,05 ms	0,03 ms	0,03 ms	0,03 ms	0,03 ms	0,03 ms	0,03 ms
Decreased EDCA A	0,84 ms	0,43 ms	0,03 ms	0,03 ms	0,03 ms	0,03 ms	0,03 ms	0,03 ms
Decreased EDCA B	0,55 ms	0,48 ms	0,03 ms	0,03 ms	0,03 ms	0,03 ms	0,03 ms	0,03 ms
Detect and vacate	0,45 ms	0,06 ms	0,03 ms	0,03 ms	0,03 ms	0,03 ms	0,03 ms	0,03 ms

The Wi-Fi latency results are not included in this clause. Because UDP traffic which does not have flow control is adopted, the latency obtained basically only indicates the time frames stay in the buffer and cannot reflect the real latency performance.

Tables B.6 to B.8 contain data from simulations of scenario 2. In scenario 2, the first vehicle is 50 m away from the intersection, and there is a Wi-Fi device 10 m away from the vehicle. X and Y are the distance between the second vehicle and the intersection and the distance between the second vehicle and a Wi-Fi device respectively. In the simulation, both X and Y have 5 variation values from 5 m to 25 m and for each pair of X and Y configurations, 5 simulations are conducted with different random seeds for each pair of X and Y configuration. The results from each run of the simulation are averaged.

Table B.6: ITS PER performance under intersection collision avoidance scenario 2

ITS device	X = 5 meters				X = 25 meters			
	Y = 5 meters		Y = 25 meters		Y = 5 meters		Y = 25 meters	
	Transition	Mitigation	Transition	Mitigation	Transition	Mitigation	Transition	Mitigation
Mitigation OFF	99,69 %	NA	99,69 %	NA	99,69 %	NA	99,69 %	NA
Reduced EDCA	86,03 %	55,07 %	98,61 %	75,06 %	88,11 %	62,42 %	97,98 %	79,13 %
Decreased EDCA A	85,00 %	15,17 %	97,06 %	21,65 %	88,61 %	25,66 %	96,96 %	30,40 %
Decreased EDCA B	59,89 %	15,23 %	73,72 %	20,51 %	63,07 %	25,37 %	76,37 %	30,02 %
Detect and vacate	50,89 %	10,59 %	80,20 %	10,98 %	56,98 %	21,32 %	77,61 %	21,71 %

Table B.7: Wi-Fi PER performance under intersection collision avoidance scenario 2

Wi-Fi device UDP traffic	X = 5 meters				X = 25 meters			
	Y = 5 meters		Y = 25 meters		Y = 5 meters		Y = 25 meters	
	Transitio n	Mitigation	Transition	Mitigation	Transition	Mitigation	Transition	Mitigation
Mitigation OFF	0,10 %	NA	0,10 %	NA	0,14 %	NA	0,12 %	NA
Reduced EDCA	0,07 %	0,08 %	0,03 %	0,10 %	0,05 %	0,05 %	0,10 %	0,07 %
Decreased EDCA A	0,04 %	0,08 %	0,06 %	0,08 %	0,04 %	0,08 %	0,06 %	0,04 %
Decreased EDCA B	0,00 %	0,03 %	0,00 %	0,02 %	0,01 %	0,03 %	0,00 %	0,02 %
Detect and vacate	0,00%	NA	0,00 %	NA	0,00 %	NA	0,02 %	NA

Table B.8: ITS latency performance under intersection collision avoidance scenario 2

ITS device	X = 5 meters				X = 25 meters			
	Y = 5 meters		Y = 25 meters		Y = 5 meters		Y = 25 meters	
	Transition	Mitigation	Transition	Mitigation	Transition	Mitigation	Transition	Mitigation
Mitigation OFF	5,86 ms	NA	5,77 ms	NA	5,81 ms	NA	5,62 ms	NA
Reduced EDCA	2,27 ms	2,06 ms	2,22 ms	2,05 ms	2,31 ms	2,00 ms	2,33 ms	2,04 ms
Decreased EDCA A	0,96 ms	0,81 ms	0,53 ms	0,09 ms	0,59 ms	0,64 ms	0,99 ms	0,79 ms
Decreased EDCA B	1,84 ms	0,49 ms	0,41 ms	0,18 ms	0,42 ms	0,25 ms	0,15 ms	0,72 ms
Detect and vacate	0,54 ms	0,11 ms	0,48 ms	0,03 ms	0,62 ms	0,03 ms	0,58 ms	0,03 ms

B.2.6 Fixed MCS for RLAN

While not necessarily reflective of actual deployment, MCS for RLAN links is fixed in the simulations. This makes comparisons of output with different parameters simpler because MCS selection algorithms can have interesting effects on the results that are due to the choice of algorithm. At this time, the MCS selection algorithm choices that are built into the model are not accurately reflective of the real, sophisticated algorithms in deployed products. If and when there is additional time, those algorithms can be modified to provide an increase in the realism factor of the simulation. Currently, given the static positions of the nodes in the simulations, a static MCS choice is a reasonable assumption when considering that while interference is not static, most deployed products' MCS selection algorithms rely on interference-free link measurements and/or passing vs failing transmission outcomes as their main inputs. The first measurement is generally independent of the interference because it is data that is collected during multiple successful receptions (i.e. presuming little or no interference, otherwise the reception would have failed and therefore would not have been used for such a measurement). The second measurement does account for interference because in the presence of interference, some packets are lost, but by examining the general level of failures in the simulation results, the validity of the fixed MCS configuration can be established (i.e. a very high level of failures would indicate that the fixed MCS is not as reasonable).

B.2.7 Additional scenarios

This clause includes results for PER for various mitigation techniques using a much larger scenario both in physical topography and node count than in the previously presented data. Example simulations for RLAN Channel = CH173 (20 MHz Channelization) and ITS-G5 Channel CH172 (10 MHz Channelization) using each of the proposed mitigations and with mitigation off have been included below for discussion. Details on the layout and node count appear within this clause.

The basic scenario is of two streets with a single intersection where the streets cross. Vehicles are placed in various locations on the streets, including in the traffic lanes for both streets and parked on the sides of each street. Mimicking an urban environment, a building is assumed to be continuously present on both sides of each street. Spacing for a sidewalk exists between the parking lanes of the streets and the building walls. RLAN Access Point devices are placed at some number of the four corners, within the confines of the building walls. RLAN client devices are randomly placed at locations both inside of the building walls and outside of the building walls within a specified radius of the Access Points. Additional RLAN devices are placed in some of the vehicles.

For each scenario there is a plot detailing PER for both RLAN and ITS-G5 and a table showing the aggregate PER statistics for ITS-G5 devices from 10 simulation runs with 10 different randomizations as described below.

Three different topologies representing different numbers of ITS and RLAN devices were created, but the data presented are for a single topology, T2, noting that some plots are presented for the T0 case as an educational tool, attempting to provide a simpler case for the reader to examine while becoming familiar with the format of the results. Within the T2 topology, the placement of devices and the start times of the data flows were varied for each randomization and each randomization was simulated with each of the different mitigation methods. The additional topology variations are detailed in table B.9. A diagram showing a single randomized placement of devices is shown for each of the three topological variations.

For each simulation run, a single topology is modelled and a random seed is chosen for the run. The random seed determines the placement of devices and the start times of each traffic flow. A traffic flow is a sequence of packets transmitted between two or more stations. A traffic flow is potentially intended for reception by more than one device if the MAC address of packets in the flow is a broadcast address. The device counts and traffic parameters remain constant regardless of the random seed chosen for the run.

Where PER plots are presented, each PER plot shown is for the one selected topology (T2). All of the PER plots are taken from simulation runs that employ the same random seed so that the device placement is the same for each PER plot and the only difference then being the mitigation technique employed for that simulation run used to generate that PER plot. The PER plots are presented to provide a visual example of the difference in PER that is created by changing only the mitigation technique while holding all other variables constant.

Tabular data beneath each PER plot is an aggregation of data from all of the 10 runs for that mitigation technique using all random seed values.

While many randomizations of device placement and flow start times were simulated, the plot data included in clause B.2 is based upon using the large Topology T2, as a representative example of the qualitative results of the entire collection of simulations, except that figure B.13 is based on the topology with the smallest node count (i.e. T0) in order to provide an easier to read plot.

General notes on topology simulated:

- A single intersection is at the centre of the topology and is unchanged for all randomizations:
  - Purple lines in the topography plots are building walls.
  - Streets and sidewalks are located between the building walls (purple lines).
  - Sidewalks are located on both sides of all streets, the width of the sidewalks appears in the table.
  - Each street has parking lanes on each side of the street and two directions of traffic lanes, the number of lanes and the lane dimensions appear in the table.

- Two roadways and one intersection exist for vehicles: there is one north-south roadway and one east-west roadways with an intersection between the two roadways occurring at the centre of the topography at coordinate (0,0):
    - The topography extends 800 m total in the x and y directions, the centre of the intersection is at coordinate (0,0) and the rightmost point of the east-west street is at (0,400).
    - The roadway dimensions and placement are unchanged through all randomizations.
- Vehicles:
    - Waiting - stopped at red traffic light for north-south street flow, there are vehicles waiting on both sides of the intersection:
        - The number of waiting vehicles is fixed in each topology, and the exact position of each vehicle is randomized based on the 80 % density value as follows:
        - A matrix of 7,0 m × 3,0 m boxes is created from the edge of the intersection in the forward traveling direction (i.e. on the west side of the north-south street north of the intersection and on the east side of the north south street south of the intersection) and extending away from the intersection:
            - 7,0 m accounts for a 5,0 m vehicle and a 2,0 m separation;
            - 3,0 m is the width of each lane.
        - Half of the total waiting vehicles are placed on each side of the intersection.
        - Waiting vehicles are placed in each box in this matrix with an 80 % probability per box beginning with the boxes adjacent to the intersection and moving away from the intersection, until all vehicles have been placed.
        - The 80 % density is intended to create a variable separation between waiting vehicles, rather than a rigid, constant separation.
    - Arriving - distributed along north-south street not waiting (not mobile, i.e. does not consider motion). These vehicles are randomly placed in all of the lanes of the north south street in both directions, so some of them appear to be approaching the intersection from both directions and some of them appear to be leaving the intersection in both directions:
        - The number of arriving vehicles is fixed per topology.
        - All non-parking lanes of the north-south street are divided into a matrix of 17,0 m × 3,0 m boxes, excluding the intersection and the areas occupied by waiting vehicles.
        - Arriving vehicles are randomly placed within this matrix.
    - Parked - randomly distributed alongside of both sides of each of the north-south and east-west streets, situated in the parking lanes:
        - The number of parked vehicles is fixed per topology.
        - All parking lanes on both streets are divided into a matrix of 6,0 m × 3,0 m boxes, excluding the intersection.
        - Parked vehicles are randomly placed within this matrix.
    - Traveling - vehicles distributed along the east-west roadway (not mobile, i.e. does not consider motion):
        - The number of traveling vehicles is fixed per topology.
        - All traveling lanes on the east-west street are divided into a matrix of 12,0 m × 3,0 m boxes, including the intersection.
        - Traveling vehicles are randomly placed within this matrix.

    - The simulation is structured so that a group of 10 waiting or parked vehicles, each transmitting 1 message per second, is represented by one virtual "node" transmitting 10 messages per second. Similarly, a group of 4 arriving or traveling vehicles, each transmitting 2,5 messages per second is represented by one virtual node transmitting 10 messages per second. Table B.9 indicates the numbers of vehicles in each topology. Figures B.11 and B.12 plot the locations of each virtual node (and of the RLAN devices in the table), not of each vehicle. Similarly, the PER plots for ITS transmissions in figures B.13 to B.18 are averages over all vehicles represented by a single virtual node, not the PER experienced by a single vehicle.

- Total number of ITS devices = sum of vehicles:
    - There is one ITS device per vehicle.
    - All ITS devices are operating on the same channel.
    - There is no BSS concept within ITS operation, all ITS messages are using a Broadcast MAC address.
- RLAN:
    - Number of hotspots inside of buildings near corners, clients distributed inside and outside of buildings:
        - RLAN_BSS_Count_hotspot.
    - Number of RLAN BSSs inside of vehicles (2 or more devices in the same vehicle, e.g. AP plus at least one non-AP station).
    - RLAN_BSS_Count_vehicle.
    - The x coordinate of each RLAN hotspot client device is chosen from a uniform random distribution cantered on the x coordinate of the associated AP, with a range of ± RLAN_hotspot_x_range.
    - The y coordinate of each RLAN client device is determined similarly, using a separate parameter for the y range.
    - Separate parameters for x and y range are provided for the RLAN devices located within vehicles.
- All distances are in m.

Table B.9: Topology parameters proposed for simulation

Topology Variations	Small (T0)	Medium (T1)	Large (T2)
set RLAN_BSS_count_hotspot	2	4	4
set num_clients_per_BSS_hotspot	2	2	4
set RLAN_hotspot_x_range - maximum x distance of hotspot client from hotspot AP	12	12	12
set RLAN_hotspot_y_range - maximum y distance of hotspot client from hotspot AP	12	12	12
set RLAN_BSS_count_vehicle	3	3	6
set num_clients_per_BSS_vehicle	2	2	2
set RLAN_vehicle_x_range - maximum x distance of vehicle RLAN client from vehicle RLAN AP	1,0	1,0	1,0
set RLAN_vehicle_y_range - maximum y distance of vehicle RLAN client from vehicle RLAN AP	1,5	1,5	1,5
set RLAN_vehicle_z_drop_range range - maximum z distance (vertical offset) of vehicle RLAN client from vehicle RLAN AP (vehicle RLAN AP assumed to sit in interior of vehicle roof at 2-dimensional centre of vehicle)	1,5	1,5	1,5
set num_parked_vehicles (east-west and north-south combined)	40	80	180
set num_waiting_vehicles (north-south)	40	100	400
set num_arriving_vehicles (north-south)	16	40	64
set num_traveling_vehicles (east-west)	48	80	80
Total number of RLAN devices (Aps, clients)	15	21	38
Total number of ITS devices	144	300	724
Uplink_Fraction = RLAN traffic flow fraction that is UPLINK	0,2	0,2	0,2
Lane width	3,0 m	3,0 m	3,0 m
Number of travel lanes per direction per street	2	2	2
Number of parking lanes per direction per street	1	1	1
Sidewalk width	3,0 m	3,0 m	3,0 m
RLAN ITS detection timeout (Used for simulation purposes only and not a proposed value)	1,25 s	1,25 s	1,25 s
ITS on time	4,0 s	4,0 s	4,0 s
ITS off time	7,0 s	7,0 s	7,0 s
ITS reception radius (ITS transmission outcomes examined only for ITS devices within this radius from the transmitter)	60 m	60 m	60 m

Figure B.11 and figure B.12 show example randomized distributions of vehicles for small (T0) and large topologies (T2) at one intersection of the north-south and east-west roadways as described above. The present document does not include any simulations based upon the medium topology (T1).

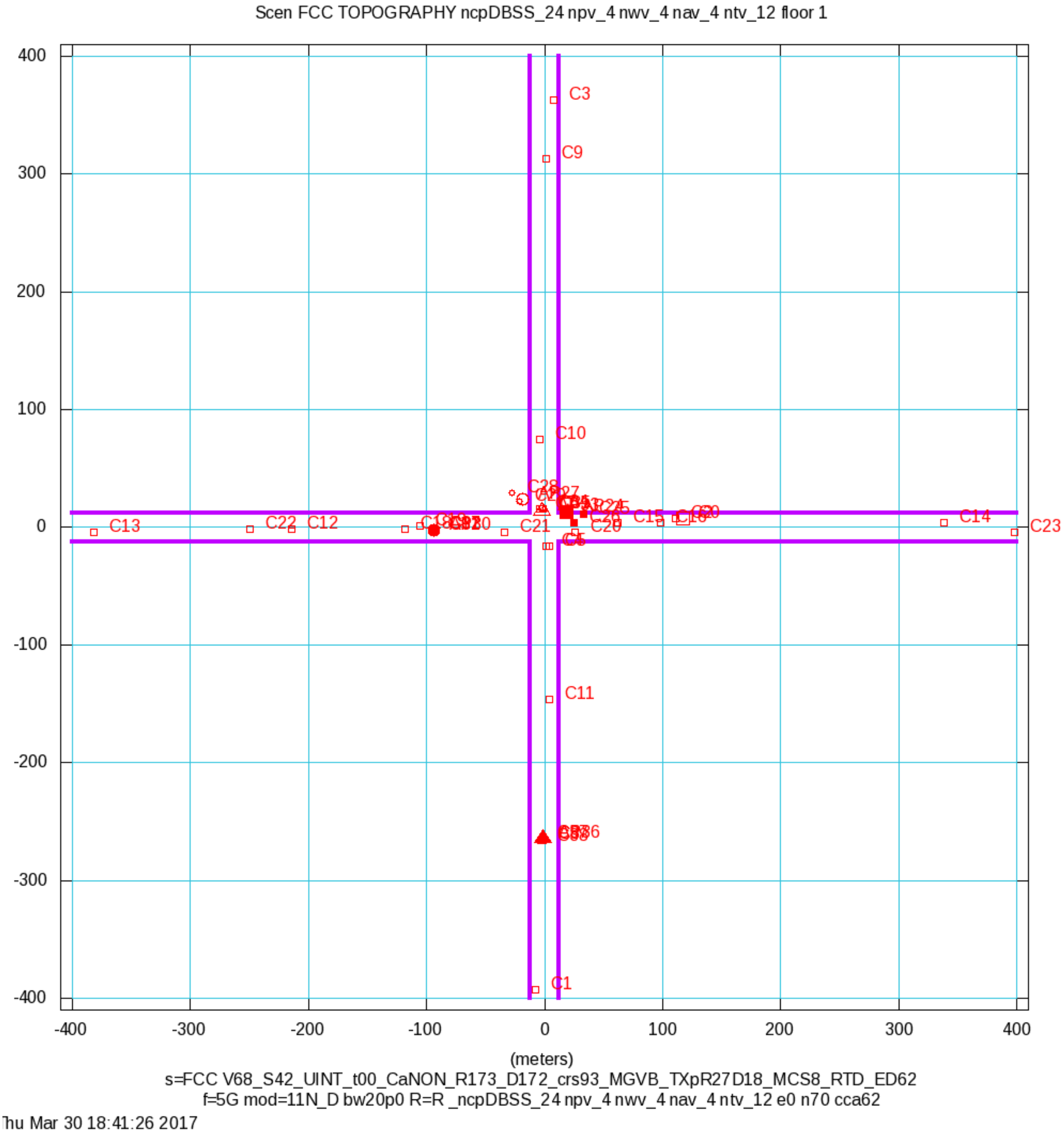


Figure B.11: Example Small Topology T0

In figure B.11, each simulated device is shown as a small shape with an associated alpha-numeric tag. Due to the density of devices, the tags overlap and become difficult to read. However, some relatively isolated devices tags can be read, and this is important for illustrating some aspects of subsequent plots. Note in particular, the location of device C9 near the top centre of the plot and device C1 near the bottom centre of the plot, as a subsequent discussion of ITS-G5 PER will refer to the devices at these locations. Red open boxes are ITS-G5 transceivers. The other shapes are RLAN devices. Each shape of RLAN device in the diagram represents a set of RLAN devices belonging to a single RLAN BSS. All ITS-G5 devices simulated are on the same 10 MHz channel. All RLAN devices simulated are on the same 20 MHz channel, but belong to several different BSSs. Three vehicles host in-vehicle BSSs (for example one of these is between -200 and -300 on the south leg of the roadway).

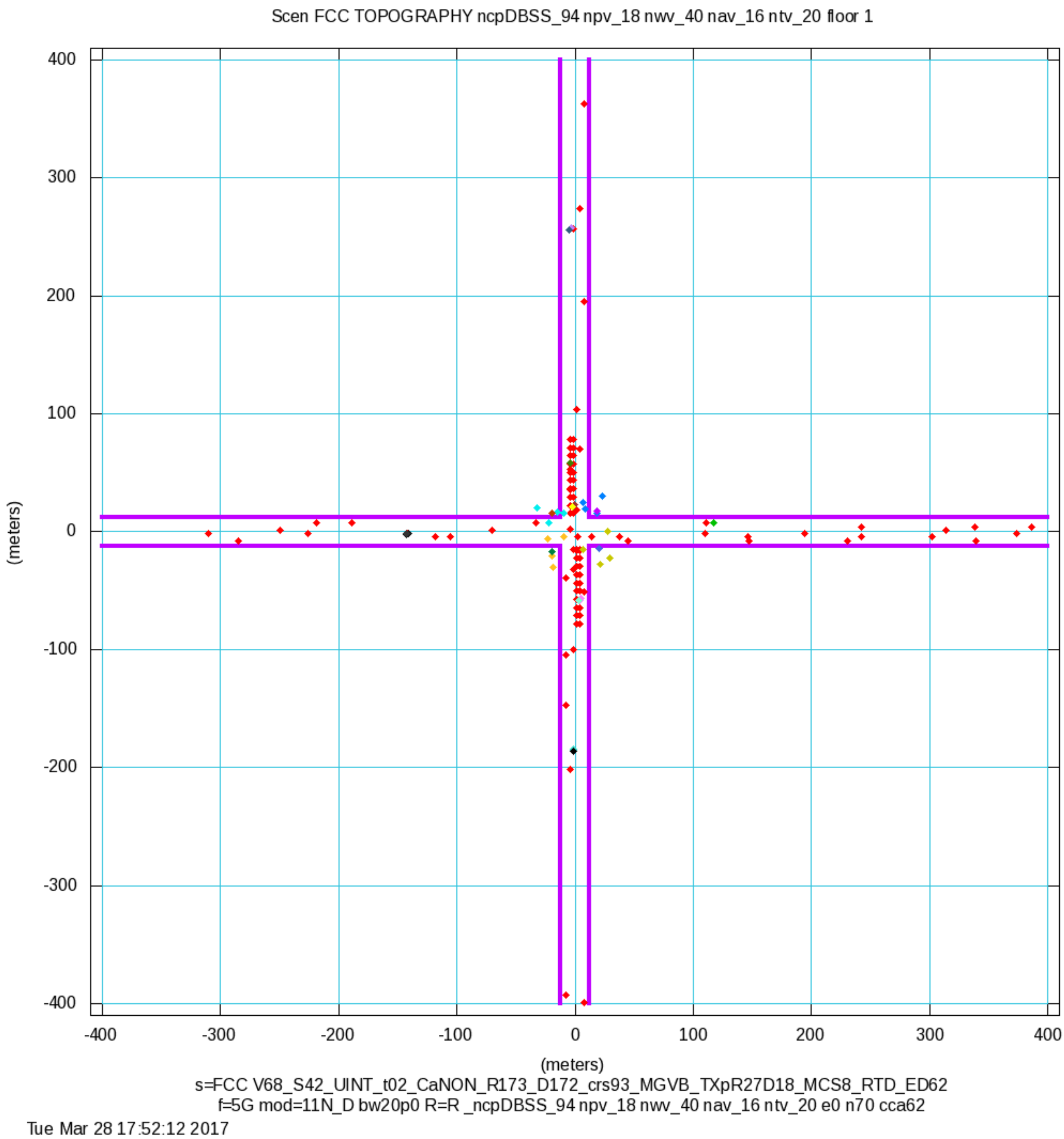


Figure B.12: Example Large Topology T2

In figure B.12, each simulated device is shown as a small diamond without a label, for clarity. Red dots are ITS-G5 transceivers. The other colours of dots are RLAN devices. Each colour of RLAN device in the diagram represents a set of RLAN devices belonging to a single RLAN BSS. Six sets of RLAN devices are coincident with an ITS-G5 transceiver, representing six in-vehicle BSSs (for example, one of these is seen near -200 in the south leg of the roadway). All ITS-G5 devices simulated are on the same 10 MHz channel. All RLAN devices simulated are on the same 20 MHz channel, but belong to several different BSSs. The density of devices is greater in this topology than in T0 and T1. Note the lines of vehicles waiting at the intersection in the north south direction.

In the simulation, the path loss models are used as shown in table B.10.

Table B.10: Path loss model use within additional simulations

Receiver	Transmitter	Model
ITS	ITS	ITS_11N_D_T
ITS	Wi-Fi	11N_D
Wi-Fi	ITS	11N_D
Wi-Fi	Wi-Fi	11N_D

The ITS_11N_D_T model is used between the transmissions of ITS devices. The original 11N_D model is used between transmissions between Wi-Fi devices and between ITS and Wi-Fi devices. The simulator is currently incapable of providing models for specific device pairing therefore all ITS device pairs use the NLOS models even if they are LOS in the topology. No additional attenuation for walls was used in the channel modelling for the results in clause B.2.

The following information applies to the result plots.

General:

- Plot name references are "Topology_RLAN channel_ITS-G5 Channel_Mitigation Used":
  - e.g. "T2 R173 D172 MGRA".
  - RLAN refers to Wi-Fi equipment.
- Mitigations simulated are:
  - MGRA = Reduced EDCA (Detect and Mitigate).
  - MGAA = Decreased EDCA Plan A (Detect and Mitigate).
  - MGAB = Decreased EDCA Plan B (Detect and Mitigate).
  - MGVB = Detect and Vacate.
  - MGOF = Mitigation Off:
    - No detection, no mitigation.

PER plots:

- ITS-G5 on/off cycle in order to create more transition events:
  - This is not standard ITS-G5 behaviour, but it is done to allow multiple occurrences of detection by RLAN to occur within each simulation run.
- Green shading = ITS-G5 active time:
  - In order to observe the amount of time needed for RLAN to detect ITS-G5, all ITS-G5 devices are cycled between OFF and ON phases of time.
  - The time period from when the first ITS-G5 transceiver is enabled for transmission during an ON phase to the time when the last ITS-G5 transceiver has transmitted during the ON phase is shaded in green. Note that because all of the plots are generated from simulations which use the same random seed, the start of the first green shaded area in each plot is the same, but subsequent green shading may differ from one plot to another as the actual transmission times of the ITS-G5 devices will be affected by activity on the air and the air activity will be different depending on the mitigation technique employed.
- Pink shading = RLAN mitigation time:
  - Once ITS-G5 devices are activated and start periodic transmissions at random phases relative to one another, RLAN devices attempt to detect the ITS-G5 device transmissions:
    - The pink shading starts when all RLAN stations successfully detect ITS-G5.
    - When at least one RLAN station has timed out since its last ITS-G5 detection event, the pink shading ends (i.e. white background).

- Where green and pink shading overlap, the green has precedence, despite all attempts to allow some level of translucence to both colours.
- The time between the start of green shading and the start of pink shading is referred to elsewhere as "transition time".
- Thin coloured lines with dots connect PER points for individual ITS-G5 transmitters = ITS-G5 PER:
  - Each ITS-G5 PPDU is broadcast to all other ITS-G5 receivers. The PER for each ITS-G5 transmitter is equal to the total fraction of failed receptions by all ITS-G5 devices that lie within a radius of 60 m of the transmitter:
    - For some randomizations, there might be no ITS-G5 devices within 60 m, and in this case, the PER is marked as 0.
      In other cases, there might be a single ITS-G5 device within 60 m, and it might be in a location where the pathloss is such that the resulting SINR yields a PER of 50 % and the PER for the transmitting device would then appear to jump between 0 and 1,0.
- Thick, solid, lines without dots represent the PER of an RLAN link:
  - Each RLAN PER line corresponds to a single unicast RLAN link in a single direction:
    - PER fluctuates and is reflective of the result only at the intended unicast-addressed recipient.
- Each ITS-G5 PPDU is transmitted with a Broadcast MAC address:
  - The results of each ITS-G5 transmission are analysed for all ITS-G5 receivers located within 60 m of the transmitter.
  - There is a separate plot line for each virtual transmitter.
  - The PER reported in the plots for ITS-G5 transmitters is equal to the proportion of correctly received copies of each transmission for all potential receivers (i.e. receivers located within 60 m).
  - e.g. where there are N ITS-G5 virtual nodes in the entire topology within 60 m of ITS-G5 transmitter, node 0:
    - ITS-G5 virtual node 0 transmits 1 ITS-G5 PPDU every 100 ms.
    - The N possible receivers of ITS-G5 node 0 each receive energy from the ITS-G5 0 PPDU:
      - If M of the N ITS-G5 nodes correctly decode the node 0 PPDU, then the reported Node 0 PER for that transmission is = 1 - M/N.
    - Each PER value is a single dot on the plot, representing the collective reception result of all PPDU transmissions from a single virtual transmitter which occurred within the time interval between dots (i.e. 0,2 s) based on the outcome of all ITS-G5 receivers in the topography within the specified range (i.e. 60 m).
- Each RLAN PPDU is generated by an instance of a layer 4 protocol (i.e. TCP) with a maximum offered load at a rate which is designed to completely fill the medium when the RLAN devices are not mitigating. The resulting packets generated by the layer 4 process are passed to the MAC instance of the transmitter and converted to Wi-Fi packets with a unicast layer 2 (MAC) address. These packets each require a layer 2 acknowledgement and are intended for a single Wi-Fi recipient:
  - For a single RLAN BSS with one AP and Y clients, there are Y+1 traffic flows with a random assignment of direction of the flow, using the Uplink_Fraction parameter from the table to determine the ratio of uplink to downlink.
  - PER is the number of failing receptions for the link vs total transmissions for the link within a time window of 0,1 s:
    - Each PER value is measured and reported for successive fixed intervals of 0,1 s and therefore, has a quantized appearance.

To allow better understanding of the PER plots, a set of PER plots using the low density T0 topology is presented to allow the reader to become familiar with the organization of the data presented in the subsequent, high density plots.

The purpose of the PER plots is to demonstrate the performance of the ITS-G5 devices in the absence of any secondary user interference and then compare that to the case of ITS-G5 performance in the presence of secondary user interference. This is accomplished by alternately enabling and disabling the ITS-G5 transmissions. While no ITS-G5 transmissions are active, the Wi-Fi devices revert to non-mitigating mode and the Wi-Fi performance under this condition can be observed. While ITS-G5 transmissions become enabled, RLAN devices are already active in the simulation and detect the ITS-G5 transmissions which are competing with the RLAN device transmissions. At some point, the RLAN devices detect the presence of the ITS-G5 transmissions and enter mitigation mode. This sequence is repeated several times within each plot.

Each ITS-G5 transmission in the simulation is a Broadcast layer 2 transmission and therefore, has no layer 2 acknowledgement process associated with it. Each of these ITS-G5 broadcast transmissions is attempted once. The outcome of such transmissions will not be directly known by the transmitter in a real situation, but in simulation, the result of each such transmission can be measured. An important metric for shared channel operation is the number of these broadcast transmissions that fail. The failure rate of the broadcast transmissions is measured as a PER value. The PER of the ITS-G5 broadcast transmissions is determined as follows.

For each single packet that is transmitted by a single ITS-G5 device, the outcome of the receive process at each ITS-G5 device located within 60 m of the transmitter is examined and statistics on those outcomes is reported in the ITS-G5 PER and latency values. In the T0 example, there are 24 ITS-G5 devices and 15 RLAN devices. Because the channel model used for ITS-G5 to ITS-G5 follows the curve shown in figure B.5, it is expected that even if no RLAN device is active in the channel, the PER will be close to 100 % between two ITS-G5 devices separated by more than 60 m. In the topology of the scenarios simulated, randomly placed ITS-G5 device can easily be separated by more than 60 m and therefore, transmissions between such distantly separated devices would be expected to fail regardless of the presence or absence of RLAN devices using the channel. Therefore, it is unfair to compare the PER of each ITS-G5 transmission as determined by examining the receive result at all ITS-G5 devices in the entire simulation. Hence, as noted, PER for ITS-G5 transmissions is determined by examining only the receive status at ITS-G5 devices which are located within 60 m of the ITS-G5 transmitter. This technique is applied regardless of the topology, but with higher densities, the number of ITS-G5 devices that will be located within 60 m of each ITS-G5 device will be statistically higher. Plot data is averaged during each 0,2 s interval.

In summary, PER for a single ITS-G5 source is the numerical average outcome of each ITS-G5 transmission for all other ITS-G5 devices that are within a circle of radius 60 m. As an example, if there are three ITS-G5 devices located within 60 m of a particular ITS-G5 device, then each dot on a PER plot for an ITS-G5 transmitter will represent the outcome of all transmissions from that ITS-G5 device within the preceding 0,2 s. The y coordinate of that dot will be equal to the PER result for those transmissions and the x coordinate represents the end time of the measurement window. In the case of 3 receivers within range, if all three receive each of the transmissions correctly, the PER is 0 %. If one of the three receivers fails to receive each of the transmissions, then the PER will be 33 %, etc. For some devices, the number of nearby receivers might be equal to 0 or 1. In the case of 0 receivers within 60 m, the PER will always be reported as 0 %. In the case of 1 receiver, the only possible values for the PER will be 100 % and 0 %. Note that with a packet generation rate of 10 Hz, there is nominally one packet transmission per ITS-G5 device every 0,1 s and so each 0,2 s measurement interval will represent the average result of two transmissions. However, due to access delay, it is possible that a single interval represents 0, 1, 2 or 3 transmissions. If access to the medium is delayed by a very long period of medium busy, then even more than 3 packets could accumulate in the transmissions queue and then, if the medium become idle for an extended period of time, all of those packets could be transmitted in series in a short time. This is unlikely, but it is possible. The simulator has the ability to discard packets at the transmitter when they have remained in the transmission queue for an excessive period of time, but that feature was disabled during these simulations. During analysis of simulation results, an upper bound on latency is applied to receptions, such that any packet on the air which is correctly received by a recipient device, but which arrives after the latency upper bound time is declared as a failing reception and counted in the PER statistics as a failure. Latency in this context refers to layer 4 latency, where the total time for delivery of a layer 4 message is measured from the point in time when that message arrives at the top of the transmitting MAC and enters the MAC queue until it reaches the top of the receiving MAC.

Within the same T0 topology, there are 15 RLAN devices sending unicast traffic using TCP. These unicast layer 2 transmissions will receive acknowledgements, and therefore, experience more reliable delivery at layer 4 than broadcast packets. However, PER is still measured for the RLAN transmissions at layer 2 because failures at layer 2 require retransmission which means that with a higher rate of failures, a lower overall throughput will be achieved. Because the RLAN packets are unicast, there is only one intended receiver for each transmission and therefore, PER data plotted for RLAN devices reflects a time-averaged PER that occurs for the packets transmitted from any one source to a specific destination RLAN device within a measurement window. That is, each single transmission will have either a 100 % or 0 % PER result because there is only one unicast intended recipient, but because the RLAN devices transmit streams of packets through time, the average of all transmission results within a time window is reported and plotted. The time window for averaging is set to 0,1 s for RLAN devices. If no transmissions occur within an averaging window, the previous value of RLAN PER is held unchanged from the previous interval.

PER for ITS-G5 devices is plotted with dots in the plot lines. PER for RLAN devices is plotted without dots. There are no ITS-G5 transmissions in the white areas of the plots, and in these periods the reported and plotted PER for the ITS-G5 devices is 0. RLAN devices do transmit during the white areas of the plots and depending on the topology, there might or might not be a non-zero PER for each transmitter.

Figure B.13 is included to allow the reader to become familiar with the PER reporting as described above.

In figures B.13 and B.14, as indicated earlier, the pink shaded area represents the time when the RLAN devices are in vacate mode (or, in figures B.15 to B.17, in mitigate mode), and therefore, the PER for the ITS-G5 devices represents the best possible PER for the given random placement of the devices, as the ITS-G5 devices during vacate mode are operating in the channel with no RLAN transmissions present. Note that the green line that alternates between 0 % PER and 100 % PER corresponds to flow 9 which is transmitted by device 9. The green line alternates between 0 % PER and 100 % PER because there is only one ITS-G5 device within 60 m of device 9. As can be seen in figure B.11 near the top centre of the diagram, that one receiver is device number 3. Therefore, whenever device 9 transmits, the PER is determined by the reception result at device 3. If device 3 receives the transmission, then the PER for that transmission is 0 %. If device 3 fails to receive the transmission, the PER for that transmission is 100 %. The PER for each transmission is equal to the number of failed receptions divided by the total number of successful and failing receptions at receivers located within 60 m of the transmitter.

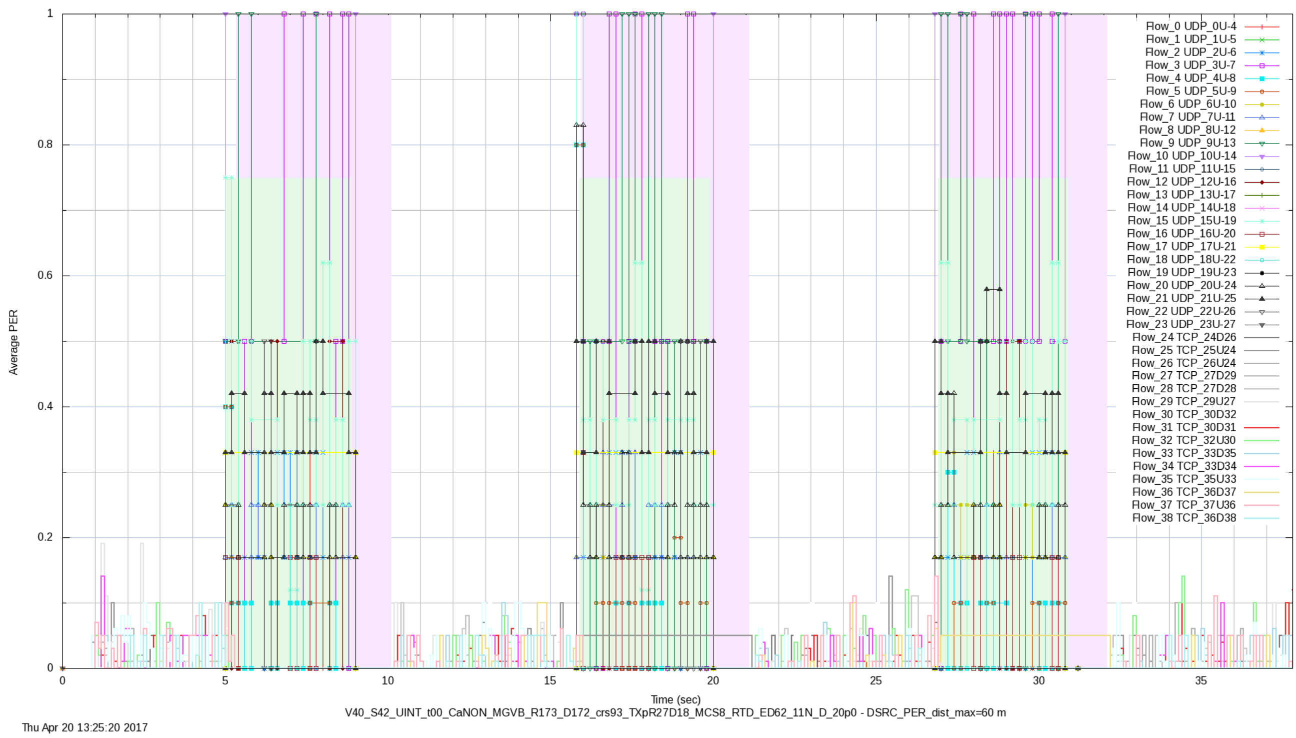


Figure B.13: T0 MGVB PER (RLAN and ITS-G5)

Table B.11 shows aggregate PER and latency statistics for all ITS-G5 devices from 10 simulation runs with 10 different randomizations, using topology T0 and Detect and Vacate method. The PER and latencies shown are calculated from all ITS-G5 transmissions during each of the mitigate and non-mitigate time periods. Only receivers within 60 m are included in the PER and latency calculations:

Table B.11: Aggregate PER and latency statistics for T0 MGVB

	SENDS	GOOD RX	FAIL RX	LAT FAILS	GOOD% %	FAIL% %	LATF% %	AVELATG ms	AVELATF ms	AVELATA ms
All RLAN devices Mitigating	27 894	63 720	19 362	2	76,7	23,3	0,0	0,52	113,72	0,52
Not all RLAN Devices Mitigating	666	1 159	725	1	61,5	38,5	0,1	1,87	169,75	2,01

SENDS is the total transmissions attempted by ITS-G5 devices during all 10 simulations runs.

GOOD RX is the total number of SENDS which were received without error and within a latency limit of 100 ms of the generation of the message at the application layer by ITS-G5 receivers located within 60 m of the transmitter.

FAIL RX is the total number of SENDS which were received with error, which were not received at all, or received without error but after more than 100 ms latency, by all ITS-G5 receivers located within 60 m of the transmitter.

LAT FAILS is the number of FAIL RX which were due solely to 100 ms latency failures.

GOOD% is GOOD RX divided by the sum of GOOD RX and FAIL RX.

FAIL% is FAIL RX divided by the sum of GOOD RX and FAIL RX.

LATF% is LAT FAILS divided by the sum of GOOD RX and FAIL RX.

AVELATG is the average latency of all GOOD RX, latency is measured from the generation of the packet above the MAC layer at the transmitter to the end of reception at the recipient MAC layer.

AVELATF is the average latency of all LAT FAILS.

AVELTA is the average latency of all GOOD RX and LAT FAILS.

Figure B.14 shows the PER results for a single simulation using the highest density topology, T2 and Detect and Vacate, so again, the PER for the ITS-G5 devices in the green areas of this plot represent the best PER that can be achieved in the channel with no RLAN transmissions present. This is the baseline performance of the ITS-G5 devices for this randomization and it should be compared to the performance shown in figure B.15 through figure B.18.

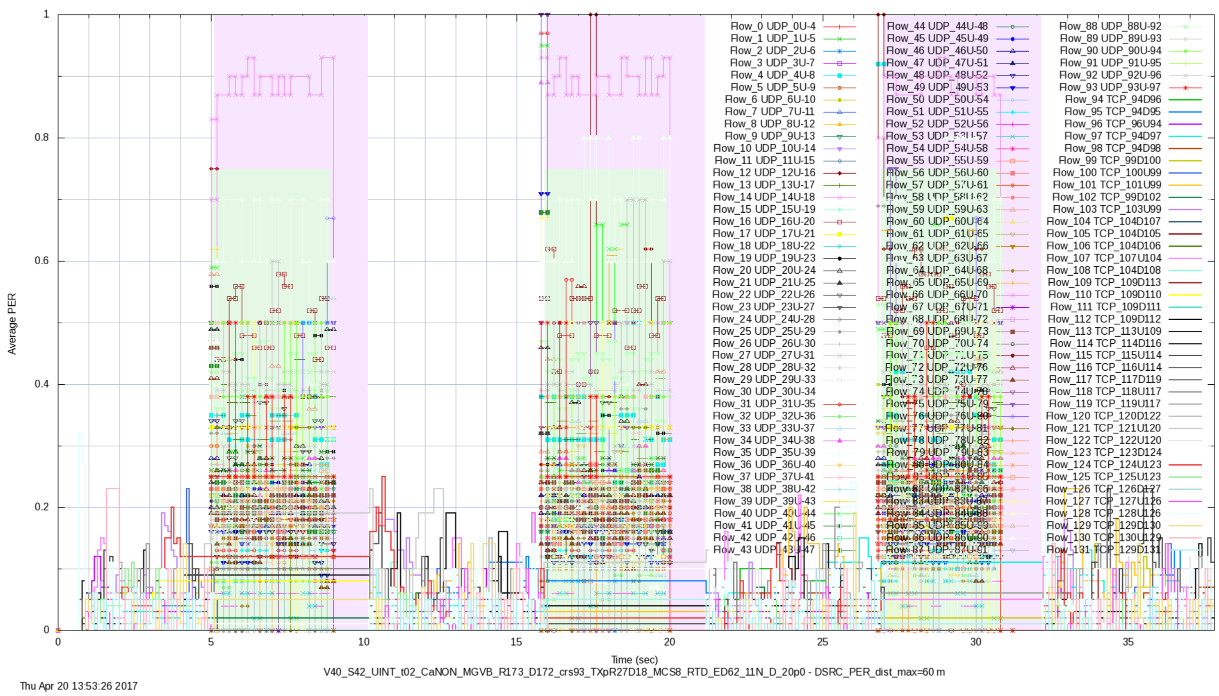


Figure B.14: T2 MGVB PER (RLAN and ITS-G5)

Table B.12 shows aggregate PER and latency statistics for ITS-G5 devices from 10 simulation runs with 10 different randomizations, using topology T2 and Detect and Vacate method. The PER and latencies shown are calculated from all ITS-G5 transmissions during each of the mitigate and non-mitigate time periods, noting again that only receivers within 60 m are included in the PER calculation.

Table B.12: Aggregate PER statistic for T2 MGVB

	SENDS	GOOD RX	FAIL RX	LAT FAILS	GOOD% %	FAIL% %	LATF% %	AVELATG ms	AVELATF ms	AVELATA ms
All RLAN devices Mitigating	110 190	1 550 719	405 813	107	79,3	20,7	0,0	0,68	116,62	0,69
Not all RLAN Devices Mitigating	1 670	18 864	10 476	0	64,3	35.7	0,0	1,50	0,00	1,50

Figure B.15 shows the PER results for a single simulation using the highest density topology, T2 and Detect and Mitigate Decreased EDCA Plan B. In this simulation there are no readily visible RLAN transmissions during the overlap between the green shaded ITS activity periods and the pink shaded mitigate periods, and therefore there is no easily discernible difference between the ITS-G5 PER in this figure and in the baseline Detect and Vacate case (figure B.14).

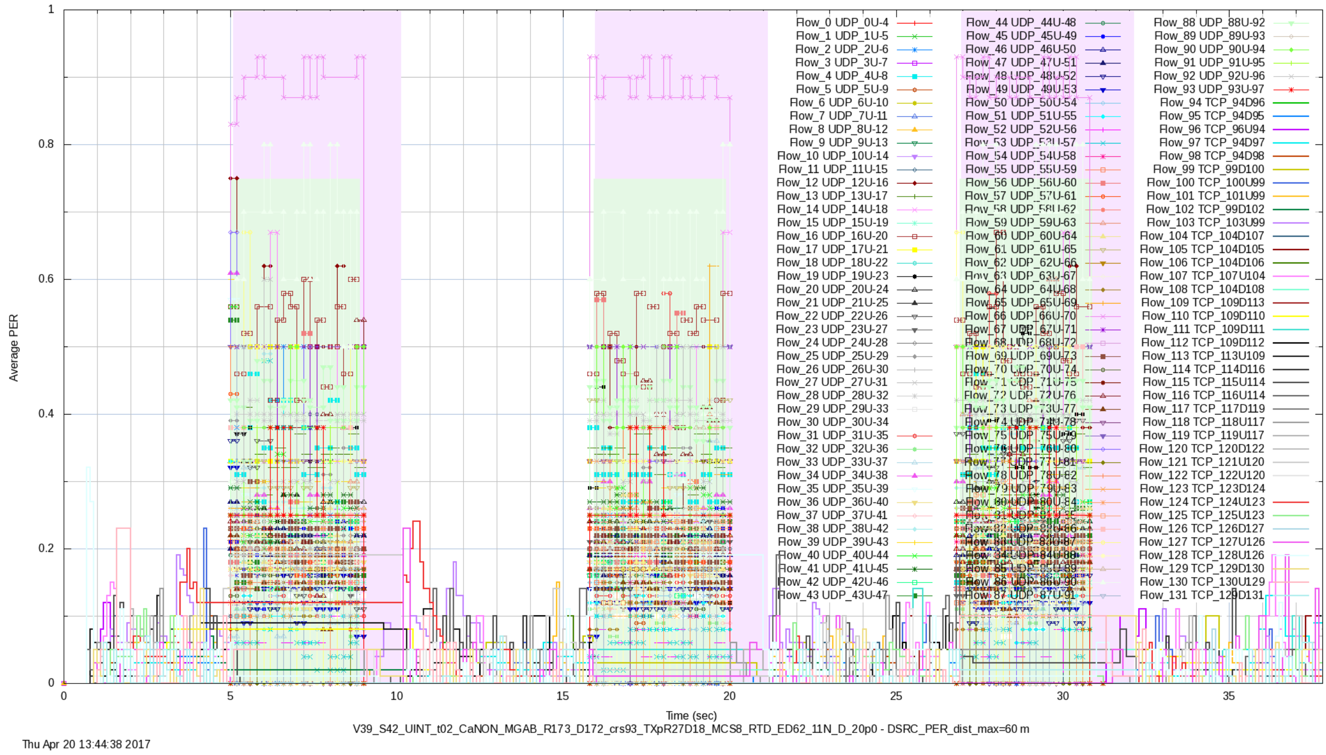


Figure B.15: T2 MGAB PER (RLAN and ITS-G5)

Table B.13 shows aggregate PER and latency statistics for ITS-G5 devices from 10 simulation runs with 10 different randomizations, using topology T2 and Detect and Mitigate Decreased EDCA Plan B method. The PER and latencies shown are calculated from all ITS-G5 transmissions during each of the mitigate and non-mitigate time periods, noting again that only receivers within 60 m are included in the PER calculation.

Table B.13: Aggregate PER and latency statistics for T2 MGAB

	SENDS	GOOD RX	FAIL RX	LAT FAILS	GOOD% %	FAIL% %	LATF% %	AVELATG ms	AVELATF ms	AVELATA ms
All RLAN devices Mitigating	110 017	1 548 050	405 063	20	79,3	20,7	0,0	0,69	118,10	0,69
Not all RLAN Devices Mitigating	1 843	21 362	11 397	2	65,2	34,8	0,0	1,04	115,50	1,05

Figure B.16 shows the PER results for a single simulation using the highest density topology, T2 and Detect and Mitigate Decreased EDCA Plan A. In this simulation there are no readily visible RLAN transmissions during the overlap between the green shaded ITS activity periods and the pink shaded mitigate periods, and therefore there is no easily discernible difference between the ITS-G5 PER in this figure and in the baseline Detect and Vacate case (figure B.14).

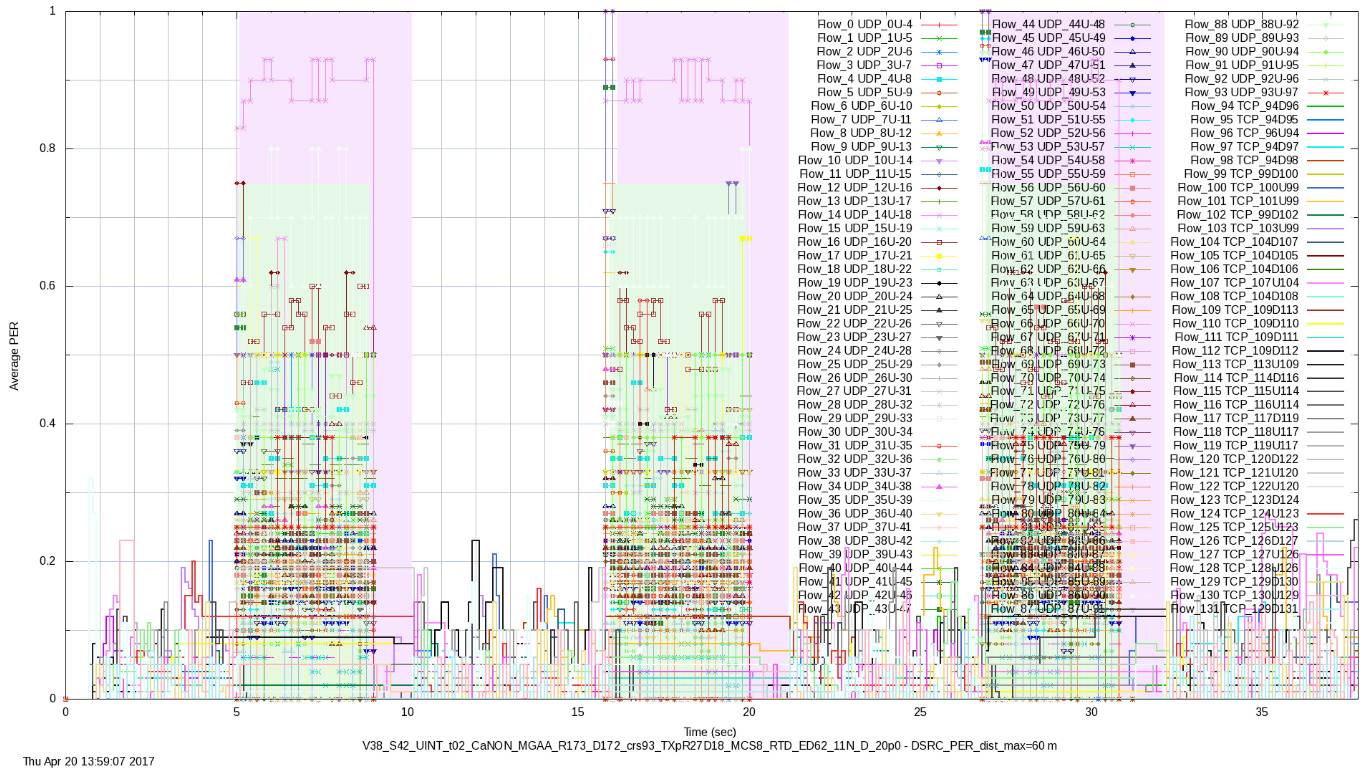


Figure B.16: T2 MGAA PER (RLAN and ITS-G5)

Table B.14 shows aggregate PER and latency statistics for ITS-G5 devices from 10 simulation runs with 10 different randomizations, using topology T2 and Detect and Mitigate Decreased EDCA Plan A method. The PER and latencies shown are calculated from all ITS-G5 transmissions during each of the mitigate and non-mitigate time periods, noting again that only receivers within 60 m are included in the PER calculation.

Table B.14: Aggregate PER and latency statistics for T2 MGAA

	SENDS	GOOD RX	FAIL RX	LAT FAILS	GOOD% %	FAIL% %	LATF% %	AVELATG ms	AVELATF ms	AVELATA ms
All RLAN devices Mitigating	109 131	1 534 619	402 317	39	79,2	20,8	0.0	0,69	131,16	0,69
Not all RLAN Devices Mitigating	2 729	30 308	18 628	4	61,9	38,1	0.0	1,38	139,79	1,40

Figure B.17 shows the PER results for a single simulation using the highest density topology, T2 and Detect and Mitigate Reduced EDCA. In this simulation, the RLAN transmissions during the overlap between the green shaded ITS activity periods and the pink shaded mitigate periods are much more frequent than they are under any of the previously depicted methods and so can be seen from the plot, the effect of these transmissions on ITS-G5 PER is clearly visible, in that the average PER lines for ITS-G5 are significantly smeared in the upward direction toward much higher PER values.

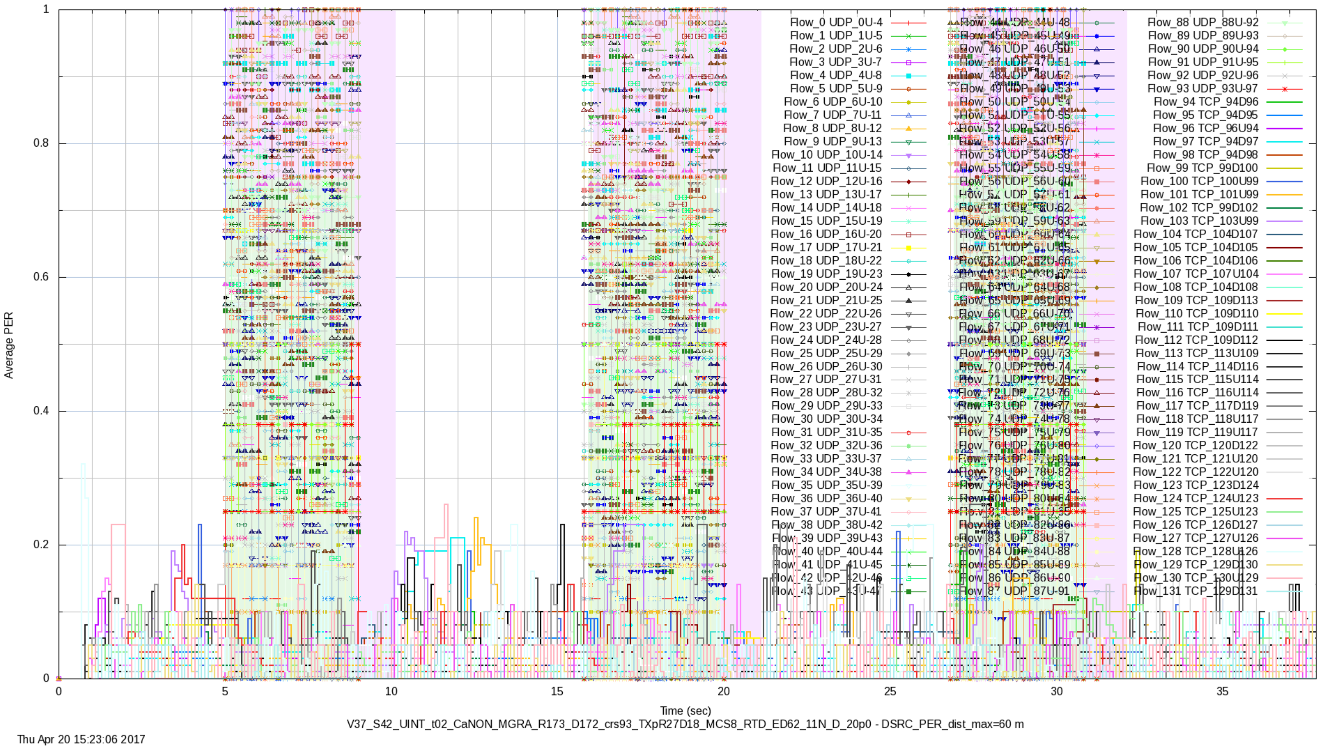


Figure B.17: T2 MGRA PER (RLAN and ITS-G5)

Table B.15 shows aggregate PER and latency statistics for ITS-G5 devices from 10 simulation runs with 10 different randomizations, using topology T2 and Detect and Mitigate Reduced EDCA method. The PER and latencies shown are calculated from all ITS-G5 transmissions during each of the mitigate and non-mitigate time periods, noting again that only receivers within 60 m are included in the PER calculation.

Table B.15: Aggregate PER and latency statistics for T2 MGRA

	SENDS	GOOD RX	FAIL RX	LAT FAILS	GOOD% %	FAIL% %	LATF% %	AVELATG ms	AVELATF ms	AVELATA ms
All RLAN devices Mitigating	108 937	834 769	1 098 687	0	43,2	56,8	0,0	1,44	0,00	1,44
Not all RLAN Devices Mitigating	2 923	19 962	32 454	19	38,1	61,9	0,0	2,45	110,40	2,56

Note that fewer ITS-G5 transmissions are reported as being attempted during the mitigation period. This is because the transition from not mitigating to mitigating takes longer when the Detect and Mitigate Reduced EDCA method is used as compared to when any of Detect and Mitigate Decreased EDCA Plan A, Detect and Mitigate Decreased EDCA Plan B or Detect and Vacate method is employed, because of the higher access probability of the RLAN devices when operating in the not-mitigating mode when using Detect and Mitigate Reduced EDCA (i.e. ITS-G5 devices will defer if they detect a medium busy condition).

Figure B.18 shows the PER results for a single simulation using the highest density topology, T2 with no mitigation technique applied. For this method, there is no change to the access probability of RLAN transmitters during the green shaded periods when ITS-G5 devices are active and so can be seen from the plot, the PER of the ITS-G5 transmissions is much higher than for any of the proposed mitigation or vacate methods as most of the dots in the PER curves associated with the ITS-G5 devices are clustered near the top of the plot. The data table B.16 confirm this observation.

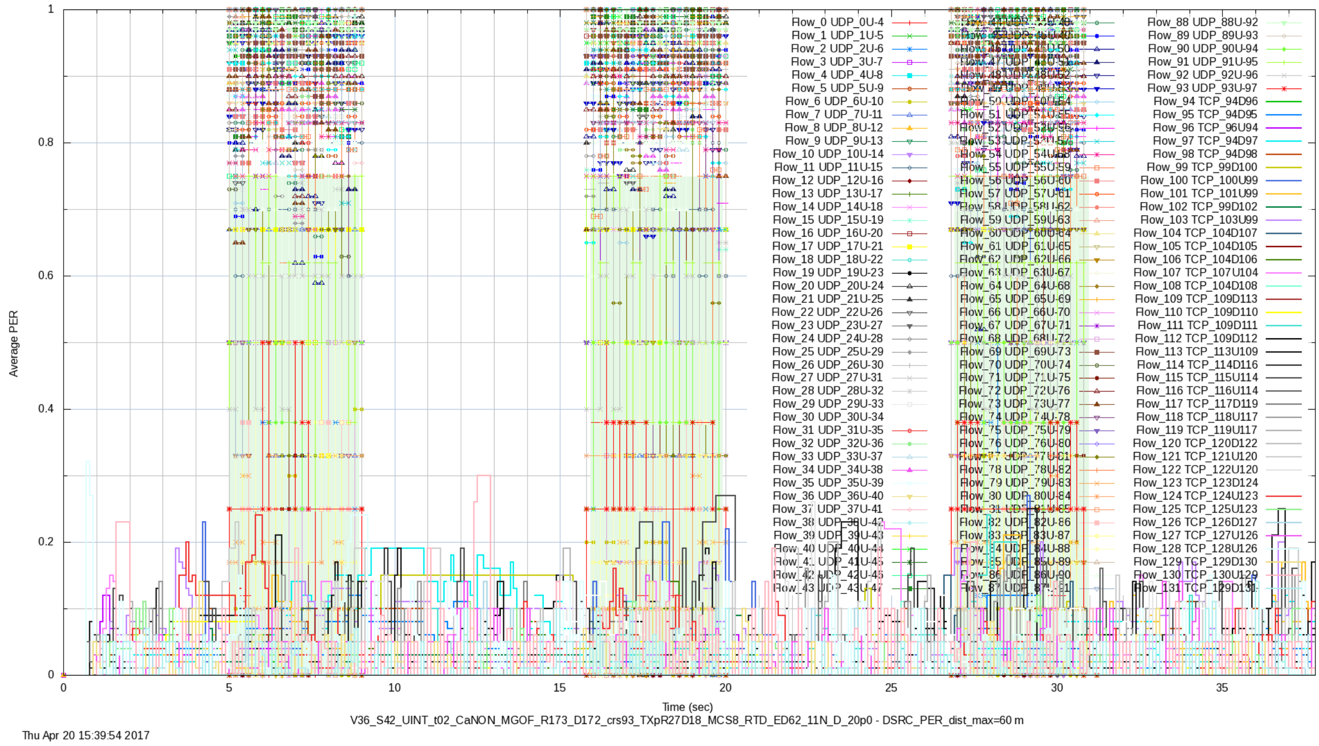


Figure B.18: T2 MGOF PER (RLAN and ITS-G5)

Table B.16 shows aggregate PER and latency statistics for ITS-G5 devices from 10 simulation runs with 10 different randomizations, using topology T2 and Detect and Mitigation Off. The PER and latencies shown are calculated from all ITS-G5 transmissions during each of the mitigate and non-mitigate time periods (note that there is no active mitigation period), noting again that only receivers within 60 m are included in the PER calculation.

Table B.16: Aggregate PER and latency statistics for T2 MGOF

	SENDS	GOOD RX	FAIL RX	LAT FAILS	GOOD% %	FAIL% %	LATF% %	AVELATG ms	AVELATF ms	AVELAT A ms
All RLAN devices Mitigating	-	-	-	-	-	-	-	-	-	-
Not all RLAN Devices Mitigating	111 860	255 498	1 730 374	6 380	12,9	87,1	0,3	10,11	173,81	14,10

Because there is no mitigation of RLAN activity in this simulation, there is no PER or latency data in the table present for the case of mitigation on.

B.3 Challenges in spectrum sharing between ITS-G5 and RLAN

B.3.1 Introduction

This annex analyses the potential challenges in enabling RLAN devices to share ITS-G5 spectrum using the spectrum sharing algorithms presented in the present document. The investigation leads to identification of a unilateral hidden terminal problem (UHTP) which exists due to the asymmetric capability of different types of devices in sensing each other's transmissions. UHTP fundamentally challenges the way of RLAN devices to share spectrum with ITS devices.

The analysis in this annex includes two parts. The first part examines the ITS transmission detection technique which is shared by both Detect and Vacate (D&V) and Detect and Mitigate (D&M). The second part focuses on understanding the influence of RLAN transmissions on the communication performance of ITS systems after ITS traffic is successfully detected.

B.3.2 Detection of ITS transmissions

Both D&V and D&M rely on detection of ITS traffic to activate appropriate mechanisms to protect ITS transmissions. The successful detection probability (SDP) depends on several factors. More specifically, when RLAN devices are transmitting, their ITS detectors cannot detect ITS traffic if there are any. The SDP is then bounded by the portion of the time where RLAN devices do not use the channel. Comparing to D&M, D&V adds an extra latency of 266 µs in channel access after a transmission longer than 2 ms. This additional delay should lead to a larger SDP for D&V than for D&M when the durations of RLAN packets exceed 2 ms. On the other hand, the two algorithms are expected to have the same SDP when RLAN devices' packets last less than 2 ms.

Another factor contributing to the efficiency of an RLAN device's detection of ITS transmissions is ITS preamble detection threshold, which is set to [-85dBm] in the present document, for its ITS detector. An ITS device needs to be close enough to a RLAN device to be preamble-detected. In some cases, such an RLAN device may be located at one corner of an intersection. In this case by the time the RLAN device can detect the preamble of an ITS transmission, the ITS device (e.g. installed on a vehicle) may have missed transmissions/receptions of ITS messages which help avoid a traffic accident. Further studies are needed to find an appropriate ITS preamble detection threshold for ITS detectors.

B.3.3 RLAN interference on ITS transmissions after detection

In order to assure RLAN devices from impacting the communications between ITS devices, RLAN transmissions should be limited to the period of time where no ITS traffic are present on the channel. After detection of ITS transmission only the D&M algorithm allows RLAN devices to use the channel. The analysis in this clause therefore focuses on the D&M algorithm.

In general, when RLAN devices share the spectrum with ITS devices after the mitigation mode is activated, two types of interference scenario may happen.

The first type of interference scenario is where the RLAN devices are not aware of ongoing ITS transmissions and therefore do not defer theirs. As shown in figure B.19, vehicle v_1 is transmitting a packet to vehicle v_2 which can decode the ITS packet with RSSI as low as -92 dBm (assuming noise floor only; no extra interference). However, a RLAN device will not detect the transmission with RSSI below -85 dBm. This means that a RLAN device with certain distance away (marked as d_1) from v_1 will not defer to v_1's transmission. Furthermore, if a RLAN device does overlap with the ITS transmission, v_2 will not be able to receive v_1's packets unless v_2 is close enough to v_1 such that the SINR at v_2 is above the packet decoding threshold. In figure B.19 this distance is marked as d_2 (which is a function of the location of the RLAN device) and obviously $d_2 < d_3$, where d_3 is the largest distance at which v_2 can receive v_1's packet without RLAN interference. In other words, the range of ITS transmission will be impacted for both D&V and D&M in this type of interference scenario.

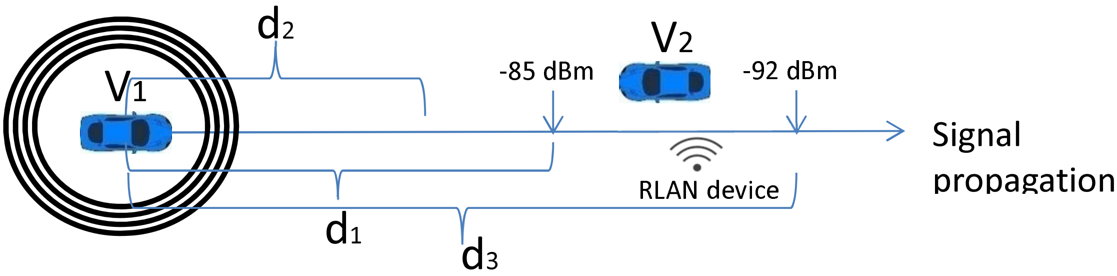


Figure B.19: RLAN interference due to limitation in detecting ITS transmissions

The second type of interference scenario is when a RLAN transmission begins, and then overlaps with the start of an ITS transmission.

As shown in figure B.20, the RLAN device starts transmission when it recognizes an idle channel. However, due to the unpredictability of ITS traffic, vehicle v_1 may have a packet to send before the RLAN transmission finishes. Since there is no ongoing ITS transmission, the vehicle's CCA function considers the channel to be idle, the vehicle initiates its transmission and a packet collision occurs. Then vehicle v_2 will not be able to receive v_1's packet unless v_2 is close enough to v_1 (marked as d_2) such that the SINR at v_2 is above the packet decoding threshold. The definition of d_3 is the same as within figure B.19.

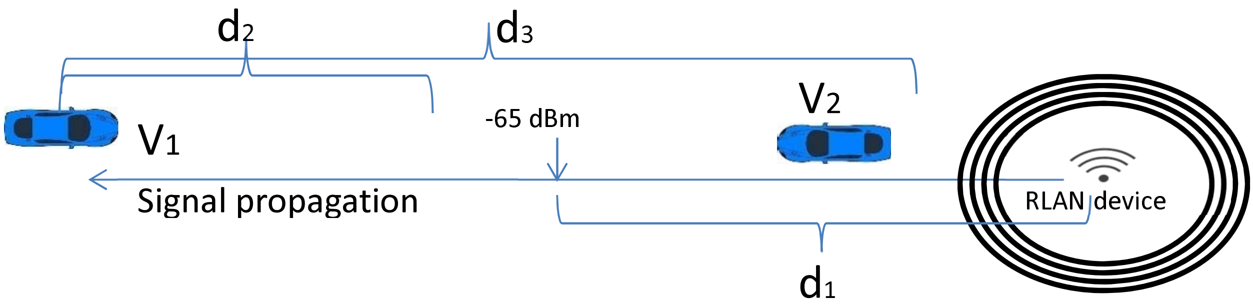


Figure B.20: Unilateral hidden terminal problem

The challenge in resolving the second type of interference is that the RLAN device's transmissions are hidden to ITS devices. When there are ITS packets to be sent, they will not defer to RLAN transmissions. This is called the unilateral hidden terminal problem.

One may note that if v_1 was within d_1 of the RLAN device, v_1 may, through energy based CCA, have sensed that the channel was busy and therefore held transmission, avoiding a packet collision. However, this requires that v1 is close to the RLAN device. Furthermore, when v1 defers and then transmits, there may still be interference from another RLAN source at v2, undetectable by v1.

An important scenario where ITS-G5 technology is expected to improve traffic safety significantly is at intersections. ITS-G5 has a NLOS communication capability, which allows vehicles to become aware of collision threats that autonomous sensors (radar, camera) cannot detect. The U.S. Department of Transportation shares the same observation [i.46] and therefore prefers to use intersection scenarios to promote the likely large scale deployment of the technology. However, communications happening near an intersection may not be as robust as on the highway due to potential lack of direct communication path between two vehicles. At distances critical for collision avoidance, the signal strength available at the receiver may result in a SINR barely above the packet decoding threshold, making the receiver vulnerable to any interference. As seen in [i.39], the communication range for a NLOS link in intersections becomes dozens of meters, largely reduced compared with hundreds of meters in scenarios with LOS conditions.

As a result, intersections form a good yet challenging testing ground for both spectrum sharing algorithms. In the present document, analysis is conducted based on such a scenario shown in figure B.21. In particular, two vehicles V_1 and V_2 move towards the center of the intersection from orthogonal directions. Building-A, which blocks the drivers in V_1 and V_2 from seeing each other, is installed with several RLAN devices indoor and/or outdoor. These RLAN devices are assumed to be running the same spectrum sharing algorithm. Boxes B, C and D represented with dotted lines in figure B.21 are placeholders for potential buildings so that figure B.21 can cover different types of intersections (e.g. fully closed intersection, ¾ closed intersection, etc.). For the purpose of discussion, it is assumed that w_1 and w_4 may not always detect each other's transmissions.

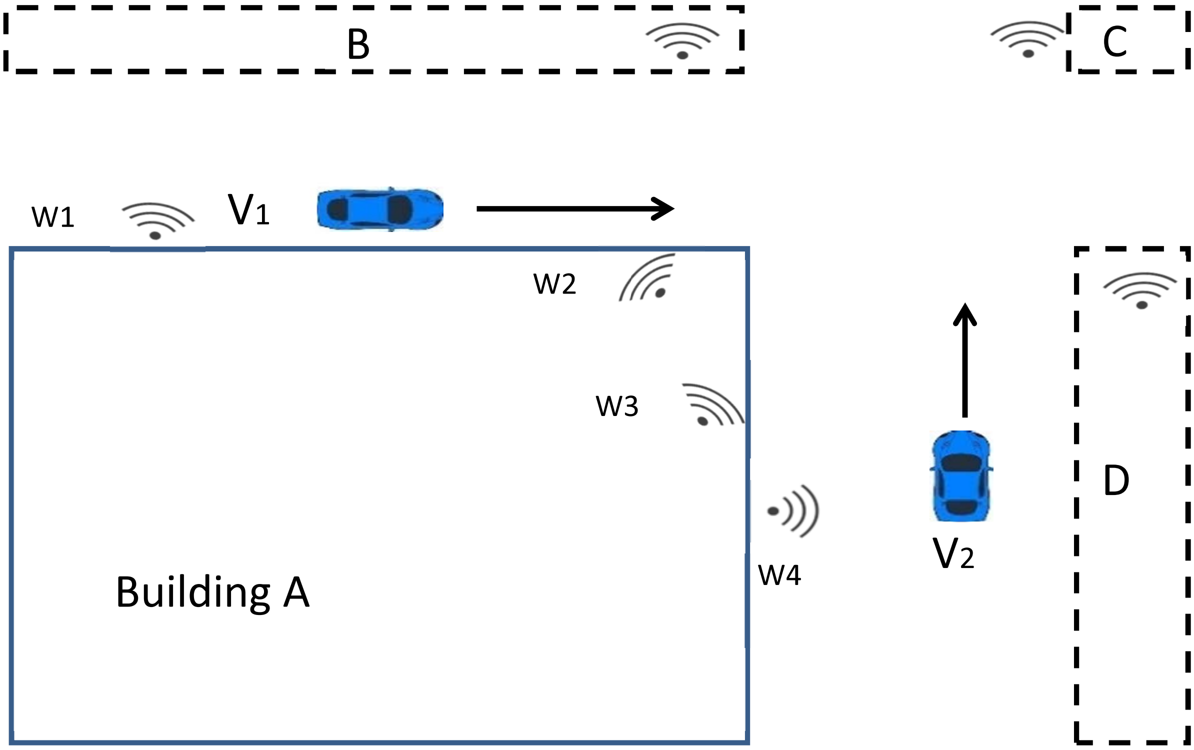


Figure B.21: Vehicles approaching an intersection

Interference analysis for D&M

According to D&M, after ITS traffic is detected on the channel, a special set of EDCA parameters will be applied for 2 s to RLAN transmissions. In figure B.22 t_0 is marked as the time at which an ITS transmission is detected by all the W1 to W4 RLAN devices in figure B.22. After t_0, due to the periodicity of ITS transmissions, the channel will be unused, from the perspective of ITS devices, for some period of time. RLAN devices manage to access the channel with special EDCA parameters. In this analysis, the case where the two vehicles have messages to send precisely at the same time is ignored.

When ITS devices have messages to transmit again (e.g. t_1, t_2, t_4), two possible cases can happen. The first case is that the ITS message gets transmitted immediately with no delay. This occurs because either no RLAN devices are using the channel or RLAN devices are using the channel but the energy-based channel busy assessment on ITS devices is not triggered. The latter reason will result in a packet collision (as shown at t_1 in figure B.22) between RLAN transmission and ITS transmission, yielding a possible packet loss (unilateral hidden terminal collision). The probability of having unilateral hidden terminal collision is as high as the percentage of time during which RLAN traffic occupies the channel. In other words, if in figure B.21 RLAN devices (W1 to W4) heavily use the channel, even with a special set of EDCA parameters, the probability of ITS transmissions overlapping with RLAN traffic approaches 1.

The other scenario that may happen when ITS devices try to access the channel is that the transmission of ITS message is delayed because the energy from RLAN traffic triggers CCA of ITS devices to indicate a busy channel. In other words, RLAN devices may be visible to an ITS transmitter through CCA energy detection, helping avoid simultaneous transmissions. However, this does not indicate that reception of ITS message is free of interference from RLAN devices. As an example, vehicle v_2 has a ITS message generated at t_2 but sees a busy channel due to w_4's transmission; v_2 defers the transmission until w_4 finishes. However, w_1, which is far from w4, may not detect w4's usage of the channel and their transmissions may overlap. When v_2 starts transmitting a message, the ITS packet will collide with w_1's at the receiving vehicle v_1, resulting in a possible packet loss.

This scenario in which v_2's transmission collides with w1's is a variant of the unilateral hidden terminal case. The important point is that even if v_2 initially defers to a RLAN transmission (e.g. from w4), its eventual transmission is still subject to unilateral hidden node collisions and high packet loss. The use of special EDCA parameters in the RLAN devices does not mitigate this collision scenario because the devices whose transmissions collide do not share a common view of the channel status.

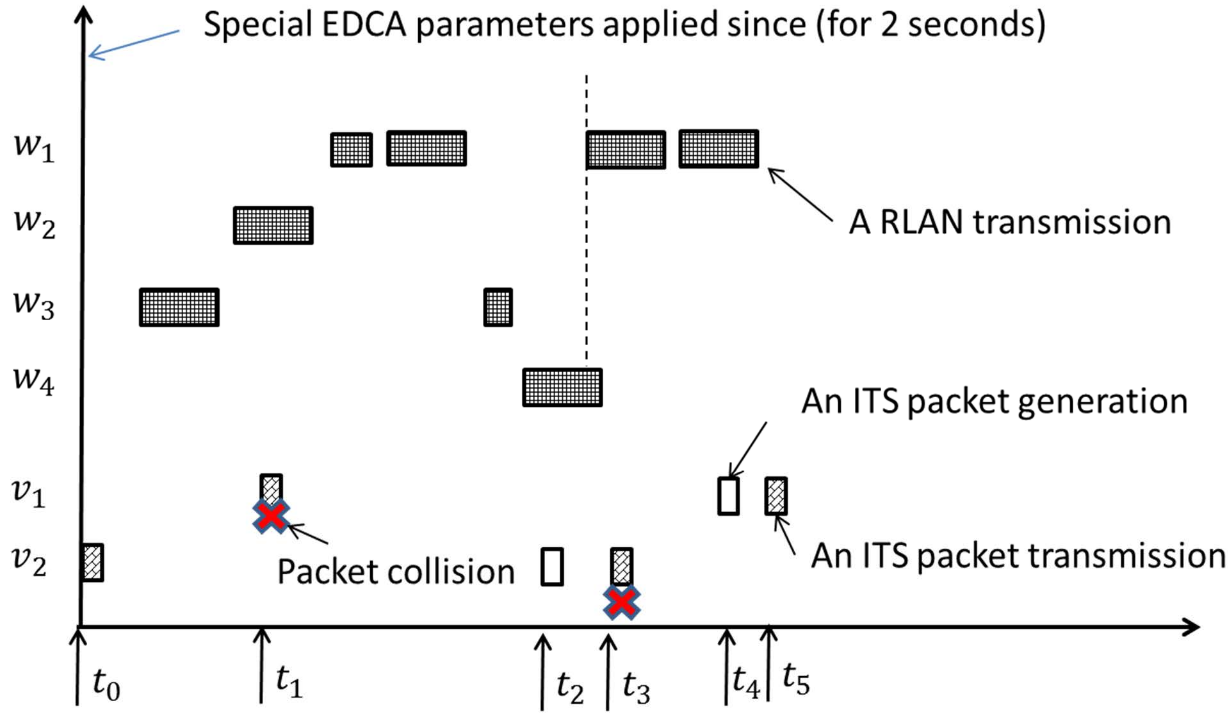


Figure B.22: An example timeline of transmissions

Interference for D&V

The D&V approach requires RLAN devices to vacate the band for several seconds once an ITS transmission is detected. This will eliminate all the packet collisions shown in figure B.22.

B.3.4 Evaluation of spectrum sharing algorithms in an indoor scenario

This part of the annex presents some NS3 simulation results as preliminary evaluation of D&V and D&M. The question of interest is to assess the effectiveness of both algorithms in protecting ITS communications. More specifically, the simulations look into the latency of RLAN devices in detecting ITS communications and the packet error ratio of ITS transmissions after RLAN devices activate vacate/mitigation mode. Note that the evaluation focuses on scenarios with in-door RLAN devices and where the vehicles are configured to keep stationary. Additional outdoor scenarios with different distributions of RLAN devices will be investigated in clause B.4.

The basic scenario used for evaluation of the spectrum sharing algorithms is shown in figure B.23. Two static vehicles equipped with ITS-G5 devices are placed on perpendicular streets of an intersection, at a distance of 25 m to corresponding stop lines. A building prevents the two vehicles from seeing each other and therefore ITS message exchanges occur through a NLOS manner. Two RLAN devices, one access point and a client device, are within the building. Both of the RLAN devices are installed with ITS transmission detectors.

A second scenario which is a variant of the basic one is also used in these simulations, as shown in figure B.24. It features two access points and two client devices placed in different buildings. Note that RLAN devices from different buildings will not be able to sense each other.

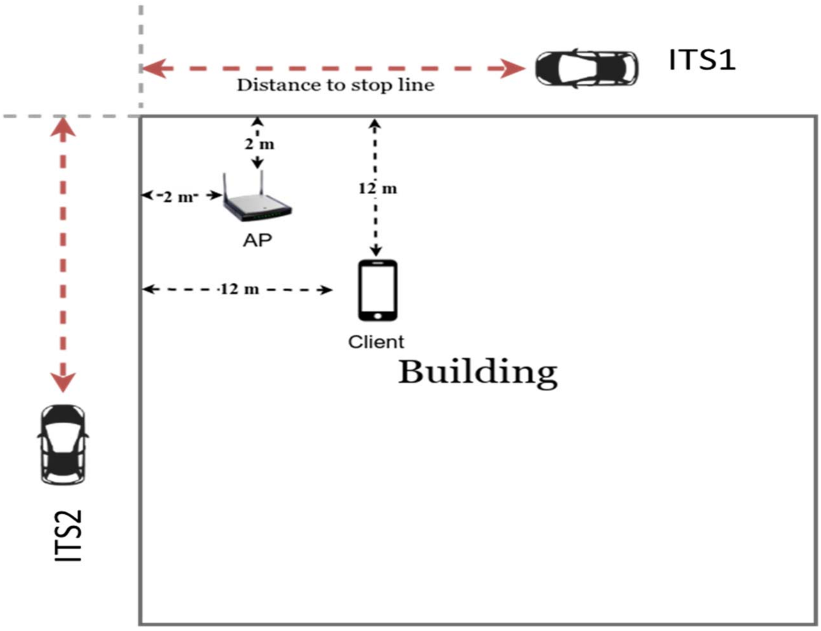


Figure B.23: Basic intersection scenario

A summary of the simulation configuration is listed in table B.17. In particular, the channel model for ITS-to-ITS communication is different from that for ITS-to-RLAN/RLAN's ITS detector channel. VisualSource11p, a calibrated model from field testing and presented in [i.44] is used for information exchanges between two vehicles. Channel model D [i.38] is used for the rest of the types of links, including ITS-to-RLAN, ITS-to-RLAN ITS detector and vice versa.

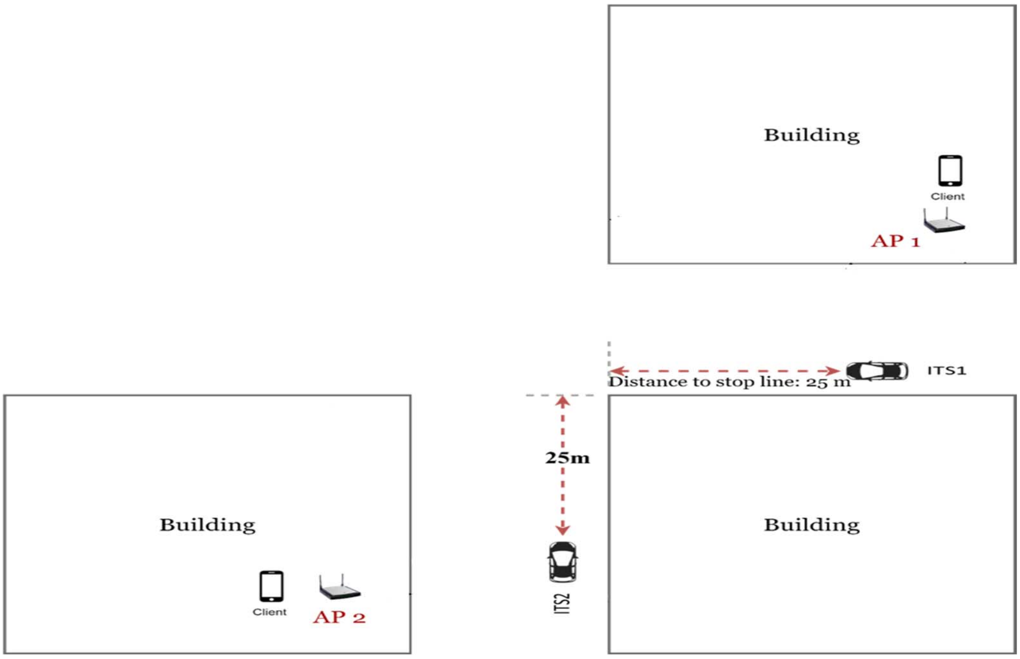


Figure B.24: Two-AP intersection scenario

Table B.17: Simulation parameters

Parameter	Value
Transmit Power	20 dBm
Message Generation Rate	ITS-G5: 2,5 Hz/10 Hz, 6,0 Mbit/s RLAN: 500 Hz (Full buffer), 250 Hz, 100 Hz, 6,0 Mbit/s
Packet Transmit time	ITS-G5: 0,5 ms Wi-Fi: 1 ms, 2,5 ms
Preamble Detection Threshold for ITS transmission	ITS-G5: -92 dBm RLAN ITS detector: -85 dBm
Mobility	Static
EDCA queue	ITS-G5: AC_BE Wi-Fi: AC_VO/AC_VI/AC_BE
Fading	As indicated in [i.44] and [i.38]
Performance Indicators	Number of ITS transmissions to first detection Packet Error Ratio (PER)
Number of runs	500

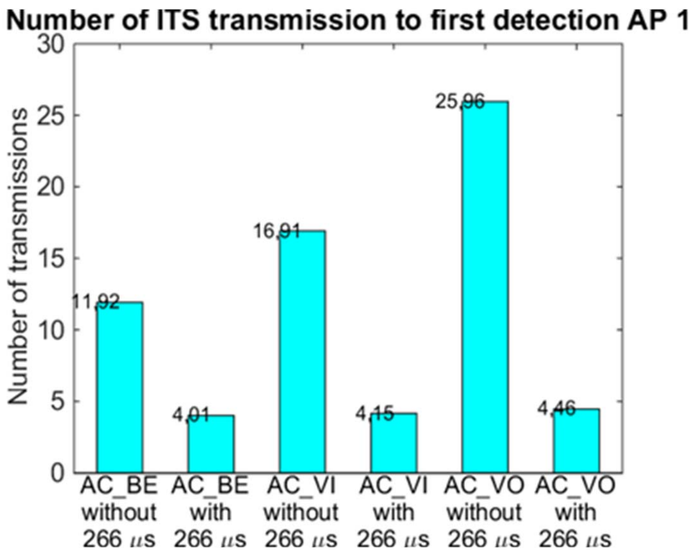
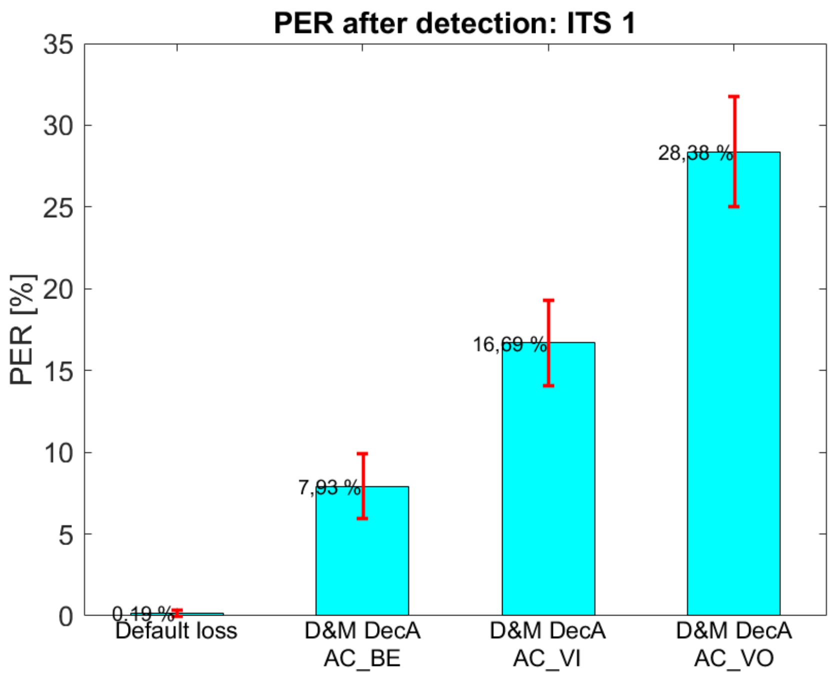


Figure B.25: The average number of ITS transmissions needed before first successful detection at AP

Figure B.25 shows the average number of ITS transmissions needed before an RLAN AP activates vacate or mitigation mode in the scenario of figure B.23. The question of interest is to see if the 266 µs extra waiting time in channel access helps improve the successful detection probability (SDP). As observed in figure B.25, when a RLAN AP uses packets with transmission duration of 1 ms, the average number of ITS transmissions needed for the AP to have the first ITS detection is around 4 times if 266 µs extra waiting time is used. However, without this period of time, the number of transmissions for first ITS detection goes up to 26, causing delay in activating appropriate mechanisms to protect ITS transmissions. Including an additional waiting time of 266 µs for all categories of Wi-Fi traffic improves the SDP.

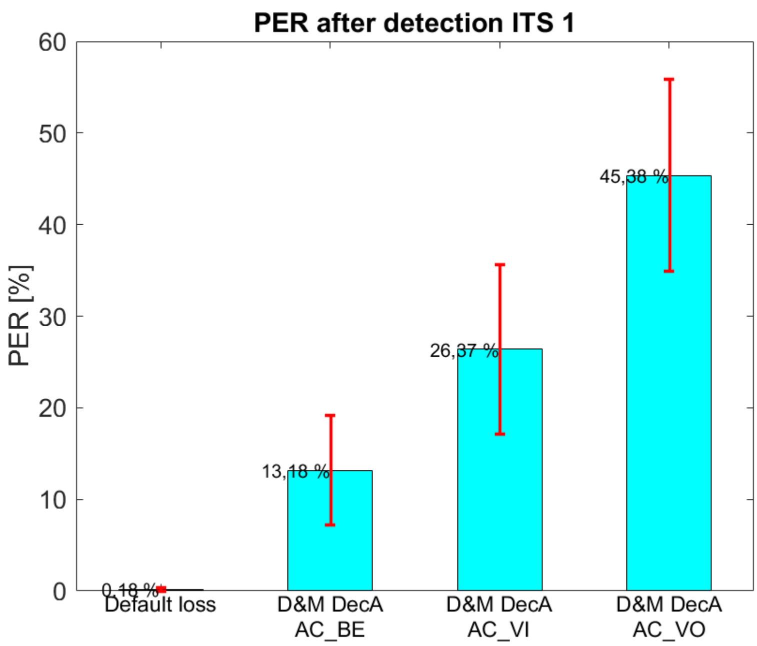
Figure B.26 shows the PER values for ITS-ITS communications after the AP in figure B.23 works in vacate or mitigation mode. More specifically, it is the PER observed at ITS2 for ITS1's transmissions. Since the distribution of vehicles are symmetrical, the PER performance for ITS2's transmission is the same with that of ITS1 and will be not presented. It can be seen that the default PER (which is also the PER using D&V) for ITS1 is only 0,2 % due to channel fading. However, when D&M is used, depending on which category of Wi-Fi traffic is applied (e.g. BE, VO, VI), the PER of ITS1's transmissions can be as high as almost 30 %. On the other hand, the simulated 8 % PER caused by AC_BE traffic would not be tolerable.

Figure B.27 shows the PER results of ITS transmissions for the two AP intersection scenario in figure B.24. Compared to figure B.26, the PERs increase for all categories of Wi-Fi traffic. The reason is that each Wi-Fi AP-client pair in figure B.24 can only sense ITS transmissions from the vehicle close by and is not aware of the existence of the far-end vehicle. As a result, when the far-end vehicle starts to transmit, the Wi-Fi AP and client will not hear it and may start a transmission as well. In contrast, transmissions of both vehicles in figure B.23 can be heard by the AP, leading to a reduced probability of overlapped transmissions.



NOTE: Decreased EDCA Plan A method is used. Wi-Fi packet duration is 2,5 ms.

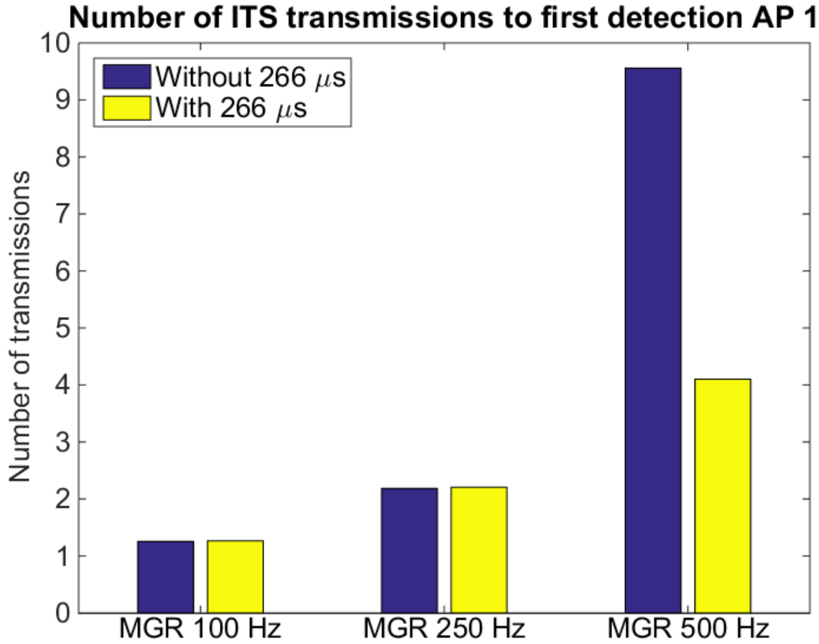
Figure B.26: PER of ITS-ITS communications in the scenario of figure B.23 after the mitigation mode of D&M is activated



NOTE: Decreased EDCA Plan A method is used. Wi-Fi packet duration is 2,5 ms.

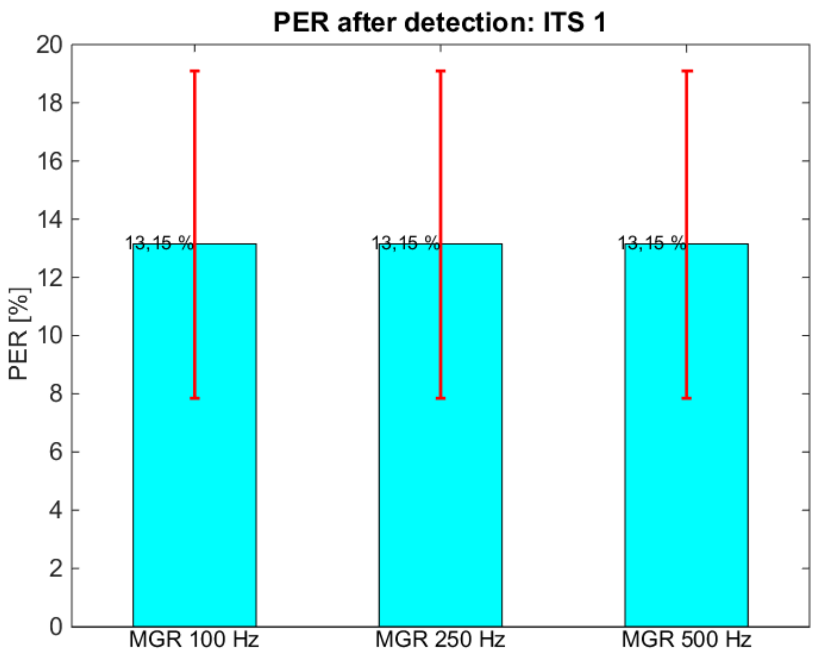
Figure B.27: PER of ITS-ITS communications in the scenario of figure B.24 after the mitigation mode of D&M is activated

The following simulation results show the influence of different Wi-Fi traffic loads on the detection delay performance and post detection PER. In particular, as the channel usage by the RLAN AP decreases, shown in figure B.28, the average required number of ITS transmissions before one can be detected by the AP drops significantly. This is expected since a larger gap between Wi-Fi transmissions lowers the probability for an ITS packet to overlap with a Wi-Fi packet. Interestingly, in contrast, after ITS traffic is detected, the PER caused by D&M remains the same for all of the evaluated Wi-Fi traffic loads. This raises concerns that even with low Wi-Fi traffic load, D&M can cause considerable performance degradation to the communication of ITS devices.



NOTE: Packets use AC_BE. Each packet lasts 1 ms.

Figure B.28: The average number of ITS transmissions needed before one is detected at AP in the scenario of figure B.24



NOTE: Decreased EDCA Plan A method is used. Wi-Fi packet duration is 2,5 ms. Packets use AC_BE.

Figure B.29: PER of ITS-ITS communications in the scenario of figure B.24 after the mitigation mode of D&M is activated

B.4 Coexistence between ETSI ITS-G5 and Wi-Fi systems in outdoor and indoor scenarios

B.4.1 Introduction

This annex provides simulation-based evaluations of the coexistence of ITS-G5 with Wi-Fi for the proposed mitigation techniques of two versions of Detect & Mitigate (DAM) called Reduced EDCA and Decreased EDCA Plan A as detailed in clause 6.5.2 and Detect & Vacate(DAV) as detailed in clause 6.5.3. The coexistence between Wi-Fi and ITS-G5 is based on two mechanisms: the 'detection' and the 'avoidance'. This annex first describes the impact of the 'detection' on the triggering of the 'avoidance', and then the performance of the 'avoidance' mechanisms behind DAM and DAV.

The study aims at first evaluating the conditions, where a coexistence issue could appear, the impact of the two coexistence strategies (i.e. prioritizing packets as in Mitigate, or leaving the channel as in Vacate) and eventually the impact of the detection asymmetries between ITS-G5 and Wi-Fi in the coexistence between ITS-G5 and Wi-Fi.

Although the study only considers the basic protocols without the slow restart extensions, it will also justify the required extensions proposed in clause 6.5.3 of the present document. It is planned to further extend the study, first considering 'slow restart' of both coexistence protocols, but also considering additional scenarios, such as the Wi-Fi AP on board of a vehicle, different vehicular traffic models (platoon, cluster, etc.), and integrating the impact of ITS-G5 congestion control (DCC) strategies.

The simulations are based on a simple intersection scenario consisting of two ITS-G5 vehicles (static or mobile) and two static Wi-Fi stations, in LOS or NLOS conditions between each other (i.e. outdoor and indoor Wi-Fi).

The first scenario has a static ITS-G5 receiver and a mobile ITS-G5 transmitter, where the static ITS-G5 receiver is placed right at the intersection. The Wi-Fi nodes are in Line of sight (LOS) conditions to the ITS-G5 nodes and a simple log-distance attenuation without fading is considered. This scenario is used to allow a deep analysis of the two protocols, and in particular the impact of asymmetric detections and unilateral hidden issues between ITS-G5 and Wi-Fi. A basic LOS fading model to illustrate the impact of fading on the detection mechanisms and the two evaluated protocols is also included.

The second scenario has two mobile ITS-G5 OBUs, both transmitting and receiving CAMs. In this scenario, the two ITS-G5 vehicles approach an intersection at constant speed. Two sub-scenarios are considered, where one models both ITS-G5 OBUs always remaining in LOS conditions with the static Wi-Fi stations, while the second includes a strong NLOS condition between ITS-G5 and Wi-Fi technologies. The first sub-scenario aims to simulate the coexistence between ITS-G5 and Wi-Fi in a typical outdoor Wi-Fi hotspot. The second sub-scenario aims to simulate the coexistence between ITS-G5 and Wi-Fi in a typical indoor commercial, corporate or residential Wi-Fi deployment. This last "Indoor Wi-Fi" sub-scenario has been found to be more challenging for coexistence, due to the difficult detection of ITS-G5 signal with strong wall attenuation. Therefore, the "Indoor Wi-Fi" scenario has also been evaluated considering a reduced Wi-Fi power, which demonstrated to be less challenging to ITS-G5 and accordingly to be a good strategy to reduce interference by indoor Wi-Fi on ITS-G5.

More detailed analysis of the study can be found in [i.47] and [i.48].

B.4.2 Evaluation scenario & methodology

Scenario 1: Static ITS-G5 Receiver, Mobile ITS-G5 Transmitter

The first scenario corresponds to the setup in figure B.30. V2 is a static ITS-G5 receiver, which always remains at the intersection. The Wi-Fi nodes are in Line of sight (LOS) to the ITS stations and corresponds to a pure attenuation case, where fading is neglected. This scenario is used to analyse microscopically the asymmetric detection and unilateral hidden issue between ITS-G5 and Wi-Fi and its impact on the coexistence.

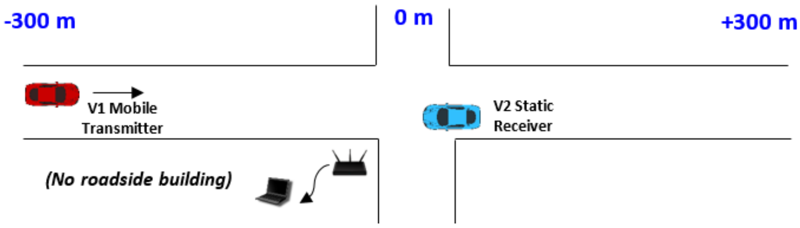


Figure B.30: Scenario - Static ITS Receiver, Mobile ITS transmitter

Scenario 2: Two Mobile ITS-G5 transmitters/receivers

The evaluation environment is illustrated in figure B.31 and figure B.32. It represents a very common urban intersection, and thereby it is an important representative scenario where ITS-G5 technology is expected to improve traffic safety. The RLAN (Wi-Fi) devices are located in the corner of the two roads. One vehicle is approaching the intersection from its west entrance and transmits CAMs to another vehicle which enters from the east entrance and might experience interference issues from the Wi-Fi devices. The channel includes fading, IST WINNER B1 - Urban Microcell; Gaussian Correlated shadowing (20 m decorrelation distance) & Ricean fast fading.

The evaluation of the coexistence is conducted considering two scenarios:

a) **Outdoor scenario -** the Wi-Fi Access Point (AP) and the Wi-Fi Mobile Station (MS) are located outside of a building and experience a weak Line-of-Sight (LOS) attenuation from transmissions sent by ITS-G5 equipped vehicles.

b) **Indoor scenario -** the Wi-Fi AP and the MSs are located inside of a building, and experience a strong NLOS attenuation from transmissions sent by ITS-G5 equipped vehicles.

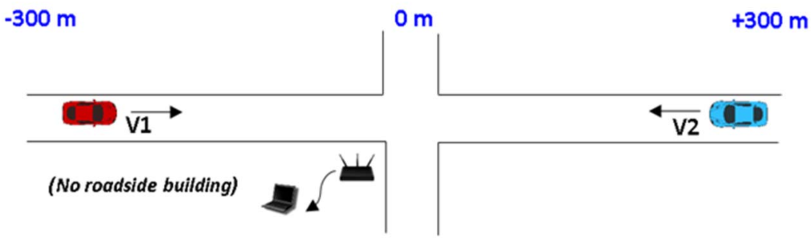


Figure B.31: Outdoor Coexistence Scenario

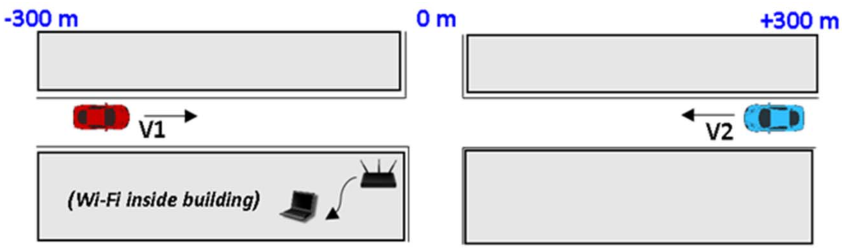


Figure B.32: Indoor Coexistence Scenario

The outdoor scenario corresponds to the case, where a café or any other open area would be equipped with a Wi-Fi AP and offering Wi-Fi connectivity to customers. The indoor scenario corresponds to the case where an indoor Wi-Fi is in use in commercial/office buildings and interferes with ITS-G5 communication. These two scenarios are typical situations, which will be experienced during a potential co-existence between ITS-G5 and Wi-Fi.

The present document evaluates the co-existence between ITS-G5 and the two mitigation techniques previously described: Detect & Mitigate (Reduced EDCA and Decreased EDCA Plan A) and Detect & Vacate.

Neither the DAV slow restart mechanism, nor the DAM Decreased EDCA Plan B has been evaluated. This is mostly due to the fact that as two ITS-G5 vehicles are modelled in a monotonic flow (with focus on the effectiveness of DAV or DAM to detect the presence of the first ITS-G5 vehicle within the Wi-Fi station's detection range) the detection remains unaffected by either DAM Decreased EDCA Plan B or DAV slow restart. To verify the effectiveness of these two extensions, the inter-arrival time between a car leaving the Wi-Fi station's detection range and the next car appearing within its range should be more than 2 s and 10 s for DAM and DAV respectively. Accordingly, this would require simulation scenarios modelling bursty vehicular traffic, which is recommended for future work.

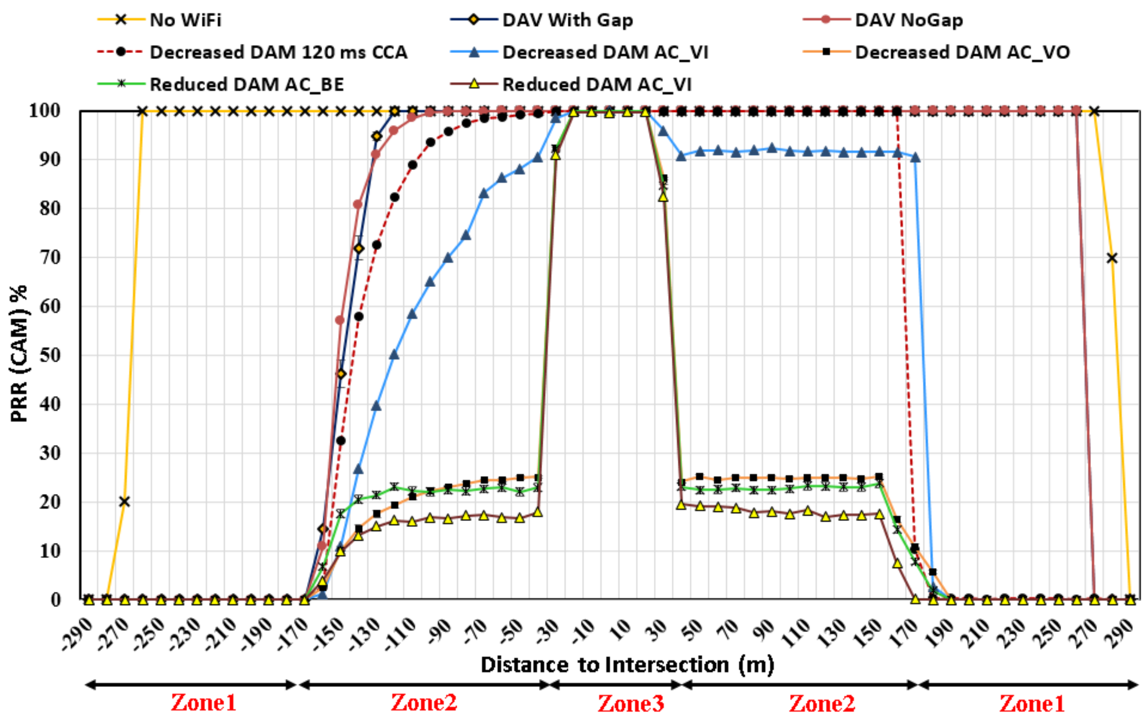
In the rest of the present document, DAM Decreased EDCA implicitly represents DAM Decreased EDCA Plan A. The complete simulation parameters are described in table B.18.

Table B.18: Simulation Parameters

Parameter	Value
Transmit Power	23 dBm
Transmit Rate	ITS-G5: 10 Hz, 300 Bytes RLAN: ~300 Hz @ 2 250 Bytes: 6,0 Mbit/s
Packet Transmit time	ITS-G5: 0,5 ms RLAN: 1,9 ms, 3 ms
Preamble Detection Threshold	ITS-G5 → ITS-G5: -92 dBm/10 MHz ITS-G5 → RLAN: -65 dBm/10 MHz RLAN → ITS-G5: -85 dBm/10 MHz
Mobility	10 ms
EDCA queue	ITS-G5: AC_BE RLAN: AC_VO, AC_VI , AC_BE
Fading	WINNER B1 [i.45] (Urban Microcell) (Correlated Gaussian & Ricean)
Performance Indicators	Packet Reception Rate (PRR) (95 % Confidence Intervals; > 1 000 runs)

B.4.3 Simulation results

Scenario 1: Static ITS Receiver, Mobile ITS Transmitter



NOTE: Where Reduced DAM and Decreased DAM stands for DAM reduced EDCA and Decreased EDCA Plan A respectively.

Figure B.33: Outdoor scenario - no fading

Figure B.33 illustrates the impact of Wi-Fi on the Packet Reception Rate (PRR) of ITS-G5 CAM transmission. In figure B.33 the x-axis represents the distance of the vehicle 1 from the corner of the crossing and thus in this scenario the distance to the AP in figure B.30.

As it can be observed, vehicles in Zone 1 (i.e. far from the intersection) will experience significant interferences from Wi-Fi, due to the higher sensitivity of ITS-G5 (-92 dBm). The distance, where this Zone is located is sufficiently far away from the intersection and the interference incurred is not expected to have significant influence on Safety-related applications. However, when vehicles move towards the intersection and enter Zone 2, Wi-Fi mitigation strategies are engaged and different effects can be observed, as function of the mitigation strategy. While a DAV or DAM Decreased EDCA mechanism immediately triggers avoidance and frees the ITS-G5 channel, the reduced EDCA creates harmful interference to ITS-G5. In Zone 2, the switching to DAM or DAV mode by Wi-Fi starts only when a CAM probabilistically coincides with a Wi-Fi non-transmission period. This probabilistic coincidence results in a gradual (not sharp) rise of CAM PRR, even if the attenuation is only log-distance without fading.

Finally, when a vehicle enters Zone 3, mitigation is engaged and no interference may be observed. However, this corresponds to a distance to intersection of 30 m, which is too short for safety-related applications. Accordingly, Zone 2 remains the critical area, where DAV or DAM intends to ensure co-existence.

Unlike the 10 s duration of DAV, DAM only lasts for 2 s (if Wi-Fi does not detect further ITS-G5), so Wi-Fi returns to normal EDCA mode within 2 s of V1 quitting the Wi-Fi detection range near +170 m, whereas DAV continues channel vacate for 10 more seconds, thereby giving a 100 % CAM PRR for 10 s or 100 m more.

The simulation is repeated by implementing fading in the channel (WINNER B1 - Urban Microcell; Gaussian Correlated Shadowing (20 m de-correlation distance) & Ricean fast fading [i.45]), the objective being to illustrate the impact of LOS fading on such coexistence.

The average attenuation of WINNER B1 model is lesser than log-distance, therefore with WINNER B1 fading, Zone 1 starts even farther than 170 m, in figure B.35. Moreover, by comparing figure B.33 with figure B.35, it can be observed that fading impacts coexistence, as it makes the strict zone separation less clear. This comes from the fact that each zone is decided by an energy level being higher than a detection threshold, for example the transition from Zone 2 to Zone 3 occurs at -65 dBm. With stochastic fading, the received signal energy is probabilistic in distance: the closer to the zone limit, the higher the probability. This effect is illustrated on figure B.34,where the smooth transition between being lower than the energy detection threshold (Zone 2) in Red, and being above such threshold (Zone 3) in Blue can clearly be seen.

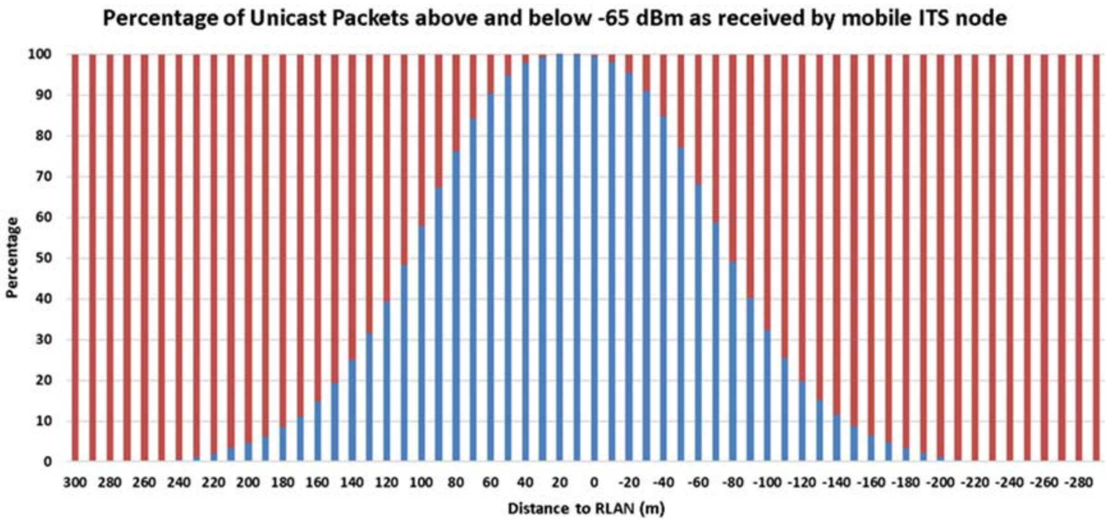
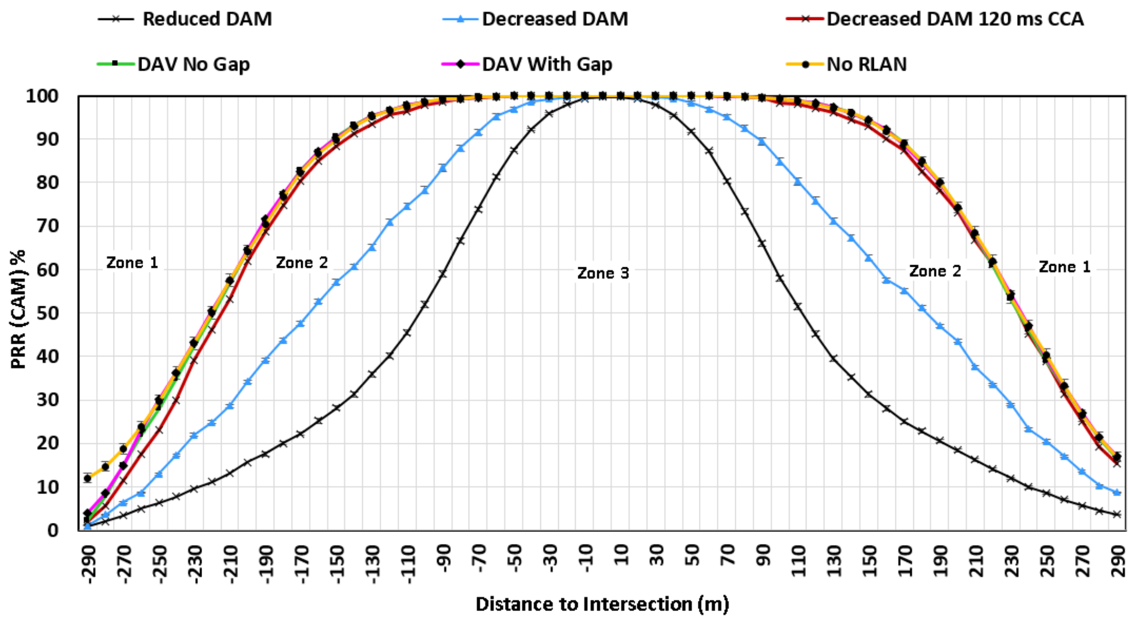


Figure B.34: Distance related to the energy detection threshold with fading - outdoor scenario

Figure B.35 confirms again the limitations of the DAM Reduced EDCA already observed on the non-fading scenario, which clearly creates harmful interference with ITS-G5. Additionally, due to the strong avoidance strategy of DAV (10 s); it only takes one ITS-G5 transmission to be detected for RLAN to vacate the ITS-G5 channel. Similarly, Decreased DAM 120 ms AIFS performs quite well, as there are more non-transmission periods (gaps) for RLAN, allowing a better detection of ITS-G5. Similar to figure B.33, Decreased DAM with just ~9 ms AIFS, might not be enough to prevent harmful interference.

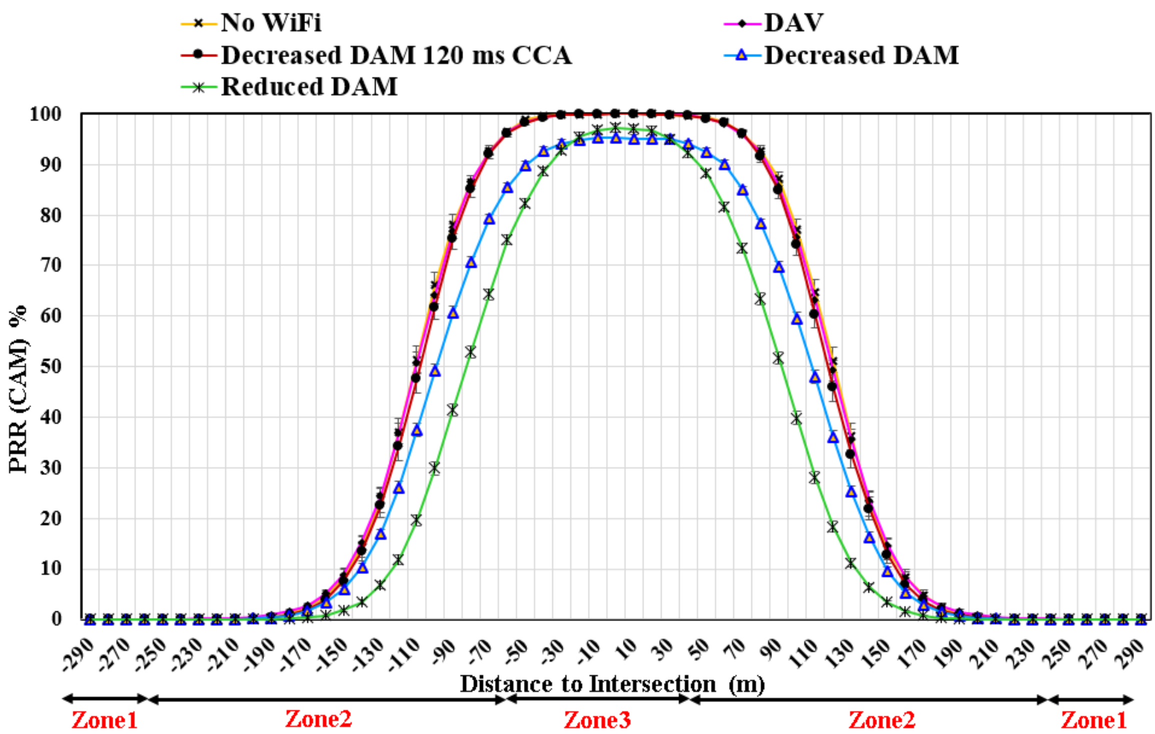


NOTE: Where Reduced DAM and Decreased DAM stands for DAM Reduced EDCA and Decreased EDCA Plan A respectively.

Figure B.35: Outdoor scenario - with fading

Scenario 2a - Two Mobile ITS-G5 Vehicles, Outdoor RLAN

This scenario has two ITS-G5 nodes V1 and V2, moving towards the intersection, both transmit and receive CAMs at 10 Hz, as shown in figure B.31.



NOTE: Where Reduced DAM and Decreased DAM stands for DAM reduced EDCA and Decreased EDCA Plan A respectively.

Figure B.36: Outdoor Scenario - with fading

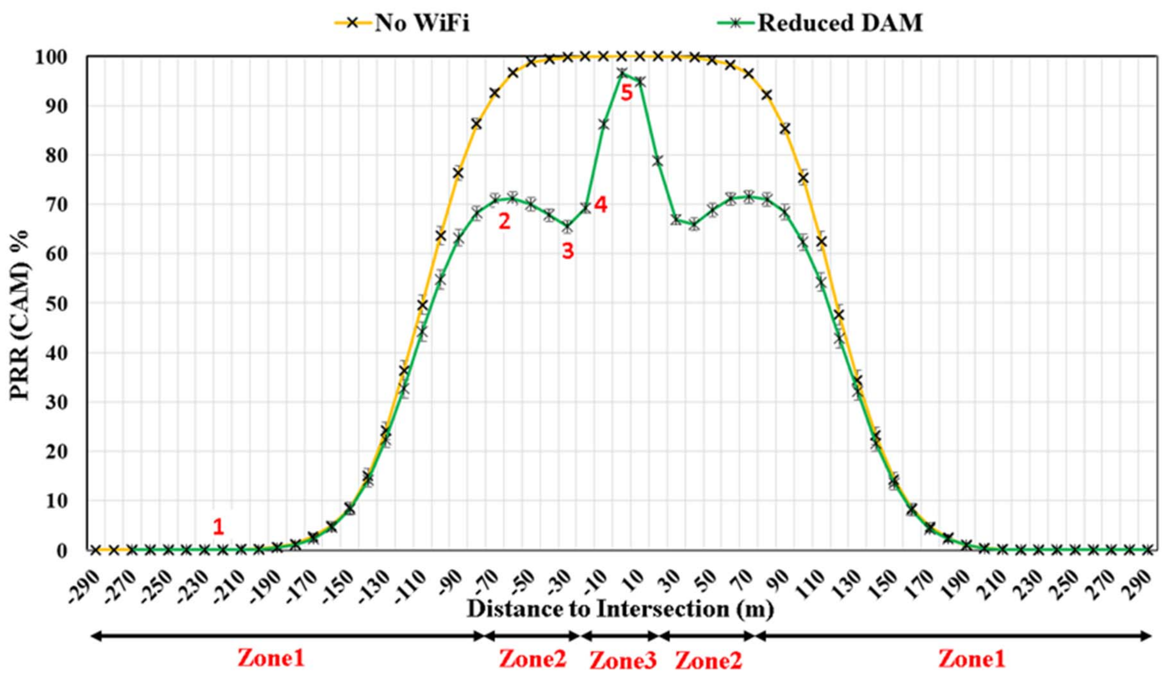
Figure B.36 shows the CAM PRR (average of both vehicles V1 & V2) for various mitigation techniques for outdoor Wi-Fi. At any point, both vehicles are equidistant to the intersection. Wi-Fi traffic of class Video (AC_VI) is only analysed and presented on the graph for the sake of readability. In figure B.35, the distance to intersection is the same as the distance between the ITS-G5 vehicles, as the ITS-G5 receiver is stationary. However, in figure B.36, the distance between the ITS-G5 vehicles is twice the distance to intersection (x-axis value) of each ITS-G5 vehicle.

Unlike the previous scenario, the receiver is mobile and the maximum CAM PRR is governed by the distance between the transmitter and receiver. As discussed earlier, the attenuation of WINNER LOS propagation is lower than the long-distance attenuation, so the start of Zone 2, i.e. the awareness range of Wi-Fi, stretches as far as -250 m.

The PRR rises gradually for the different mitigation techniques, with Reduced and Decreased DAM resulting in 10 % to 20 % CAM loss in Zone 2, compared to the curve of CAM PRR with no Wi-Fi. It even gets closer to the 'no Wi-Fi' curve in Zone 3 starting at -50 m, which indicates an increase in PRR. The curves of Decreased DAM 120 ms AIFS and DAV follow the curve of CAM PRR with no Wi-Fi, indicating their high effectiveness in preventing interference. Therefore, it can be concluded that both coexistence protocols perform relatively well in outdoor Wi-Fi scenario.

Scenario 2b - Two Mobile ITS-G5 Vehicles, Indoor RLAN

In this section an indoor scenario is analysed, where the Wi-Fi nodes are inside a building, as shown in figure B.32. Figure B.37 illustrates the CAM PRR for this case. With indoor Wi-Fi, in addition to the three zones, two other factors affect the CAM PRR, i.e. is the ITS receiver within the transmission range of the ITS transmitter and is the ITS receiver within the interference range of Wi-Fi. Figure B.37 illustrates this factor using the PRR of Reduced EDCA DAM along with the case of only ITS-G5 traffic without Wi-Fi. In this scenario, both ITS-G5 vehicles transmit and receive, but as both are symmetric around Wi-Fi, only one pair of communication is discussed.



NOTE: Where Reduced DAM stands for DAM Reduced EDCA.

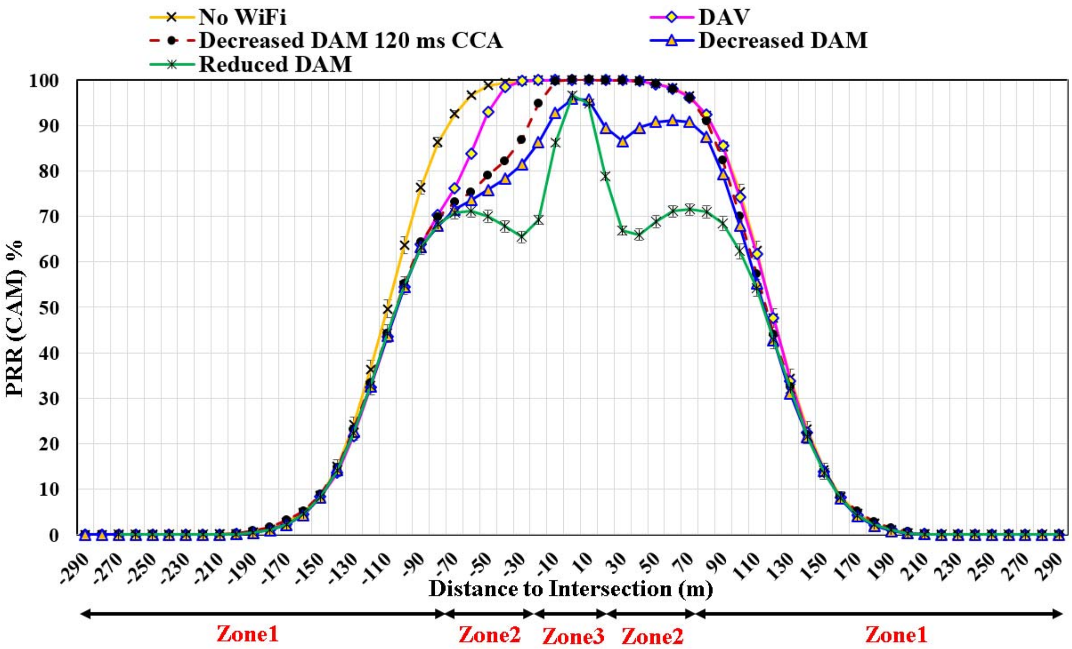
Figure B.37: Indoor Scenario - with fading

The different coexistence phases between ITS-G5 and Wi-Fi DAM Reduced EDCA may be classified as follows:

- **Point 1:** The ITS-G5 receiver (either V1 or V2) is outside the transmission range of the transmitter (either V1 or V2), so there is low PRR due to strong attenuation (irrespective of Wi-Fi).
- **Point 2:** The CAM PRR rises as the mobile ITS receiver comes inside the transmission range of the mobile ITS-G5 transmitter. Zone 2 starts at -70 m and Wi-Fi begins to detect ITS-G5, but Reduced DAM cannot fully prevent interference in Zone 2, as discussed earlier.

- **Point 3:** Unlike outdoor Wi-Fi, the PRR does not always increase in Zone 2, but there is a dip in PRR as the ITS-G5 receiver moves more and more inside the interference range of the Wi-Fi AP, i.e. the SINR of received CAMs decreases due to stronger interference from Wi-Fi. This is the point of highest interference at around -30 m.
- **Point 4 & 5:** The ITS-G5 stations move closer to the Wi-Fi nodes and detect Wi-Fi signal above -65 dBm in Zone 3 at around -20 m, causing a sharp rise in PRR.

Figure B.38 shows the performance of the different mitigation protocols (DAV, DAM Reduced EDCA & Decreased EDCA Plan A) for this indoor scenario.

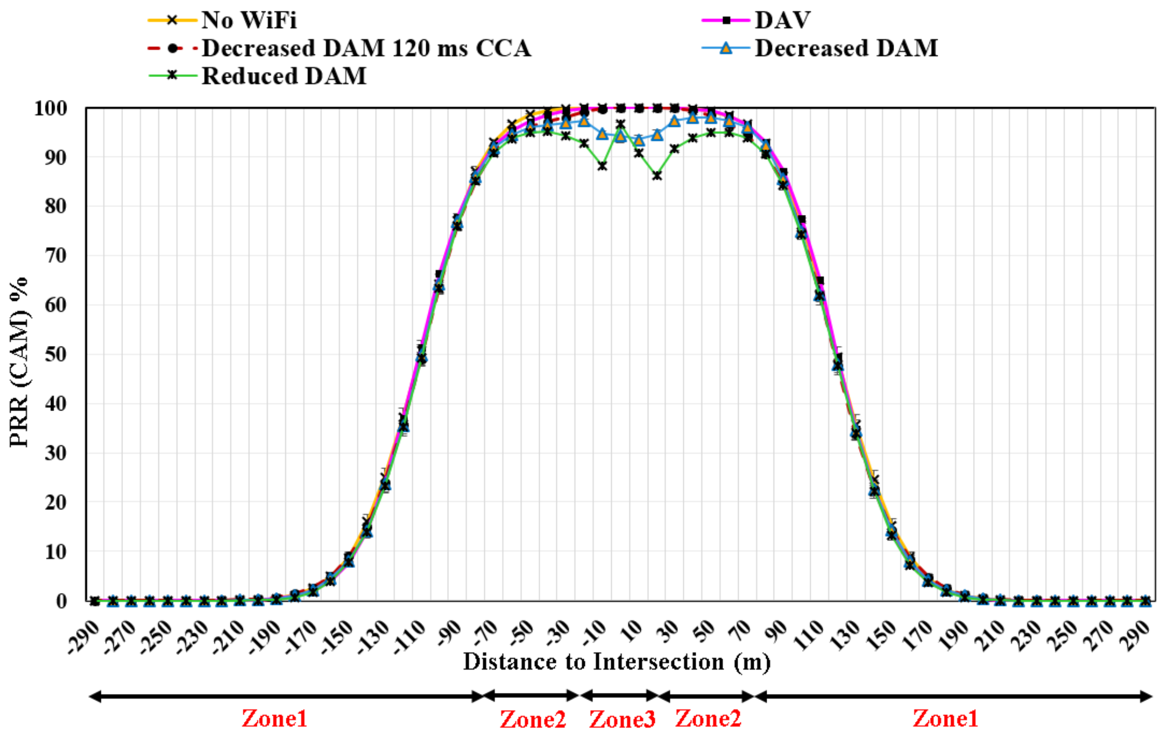


NOTE: Where Reduced DAM and Decreased DAM stands for DAM Reduced EDCA and Decreased EDCA Plan A respectively.

Figure B.38: Indoor Scenario - with fading

In figure B.38, the difference in PRR of the different mitigation techniques follows the trend of the previous section, i.e. DAV has the highest PRR and Reduced DAM produces the lowest PRR. In the outdoor scenarios, DAV achieves a PRR almost as good as when ITS-G5 operates without Wi-Fi. However, in the indoor scenario, this is not the case as the Wi-Fi node remains unaware of the ITS-G5 transmitter, unless the ITS-G5 and Wi-Fi are within 30 m.

Therefore, the detection of ITS-G5 vehicles by Wi-Fi is a significant challenge for the indoor scenario and this is regardless of the mitigation protocol. In this case DAM (Reduced EDCA and Decreased EDCA Plan A) and DAV create some level of harmful interference.



NOTE Where Reduced DAM and Decreased DAM stands for DAM Reduced EDCA and Decreased EDCA Plan A respectively.

Figure B.39: Indoor Scenario - with fading - Reduced Wi-Fi Tx Power

One aspect to notice is that beyond the generated interference, one may notice their spatial scales. All Wi-Fi induced interferences occur at distances below 70 m, which corresponds to 3 s to 5 s drive time for 70 km/h and 50 km/h respectively. In both cases, it would lead to too short a detection time by any mobile vehicle to avoid a potential impact.

In order to overcome this detection problem, one possible solution is to require Wi-Fi to reduce its transmission power. This potential scenario was configured by reducing the Wi-Fi Tx Power to 13 dBm instead of 23 dBm. Figure B.39 shows the PRR and the Wi-Fi induced interferences. It can be seen that Wi-Fi induced interferences follow a similar trend for Reduced EDCA and Decreased EDCA Plan A, although at a significantly higher PRR. It can also be seen that all other mitigation strategies, in particular DAV, do not generate any interference with ITS-G5. This is a clear indication that a reduction of Wi-Fi transmit power in the context of an indoor deployment might be necessary to mitigate interferences with ITS-G5 vehicles. The impact of such Tx power reduction on the Wi-Fi performance yet remains to be evaluated in future studies.

B.5 Summary of simulation parameters

B.5.1 Simulation parameters

Table B.19 provides a summary of the parameters upon which the simulations in the present document were based.

Table B.19: Summary of the simulation parameters used in clauses B.2, B.3 and B.4

Parameter	Value		
Simulation Reference	Clause B.2: BRAN(16)000078r2 [i.40] (superseded by data within the present document)	Clause B.3: BRAN(16)000081r3, BRAN(16)000165 [i.41]	Clause B.4: BRAN(16)000138r4 [i.42]
Transmit Power	18 dBm	20 dBm	23 dBm
Transmit Rate	Initial investigation (B.2.1 to B.2.6): ITS-G5: 10 Hz ITS message, 6 Mbit/s link rate @ 10 MHz, RLAN: 20 Mbit/s constant bit rate UDP 6,5 Mbit/s link rate @ 20 MHz, Additional scenarios (B.2.7): As above but using TCP instead of UDP for RLAN.	ITS-G5: 2,5 Hz/10 Hz, 6,0 Mbit/s RLAN: ~300 Hz: 6,0 Mbit/s	ITS-G5: 10 Hz Wi-Fi: ~300 Hz @ 2 250 Bytes 5,4 Mbit/s
Packet Transmit time	ITS: 100 bytes MSDU @ 4,5 Mbit/s RLAN: 1 500 MSDU @ 6,5 Mbit/s	ITS-G5: 0,5 ms Wi-Fi: 2 ms, 2,5 ms	ITS-G5: 0,5 ms Wi-Fi: 1,9 ms, 3 ms
Preamble Detection Threshold	ITS: -84 dBm 10 % per 1 000 bytes RLAN ITS detection: ED = -62 dBm over 20 MHz RLAN-RLAN Preamble Detection: -91 dBm (10 % PER 1 000 bytes)	ITS-G5: -92 dBm RLAN ITS detector: -85 dBm	ITS-G5: -92 dBm RLAN ITS detector: -85 dBm
Mobility	Static	Static	Receiver Static & Transmitter 10 m/s
EDCA queue	ITS-G5: AC_BE RLAN: AC_BE (but parameters varied per mitigation scheme, see annex C.)	ITS-G5: AC_BE Wi-Fi: AC_VO/AC_VI/AC_BE	ITS-G5: AC_BE Wi-Fi: AC_VI/AC_BE
Minimum AIFS	300 μs	With/without 266 μs	With/without 266 μs (D&V) Per clause C.1 (D&M)
Fading	802.11n Channel Model D (with fading included). Calibrated channel model with real measurement data.	As indicated in [i.38] and [i.44]	No fading (scenario 1) WINNER B1 (Urban Microcell) (Correlated Gaussian & Ricean) (scenario 2)
Jitter of CAM transmissions	0	±5 ms	0
Performance Indicators	ITS lost PPDUs (i.e. PER, all broadcast), RLAN throughput	Number of ITS transmissions to first detection Packet Error Ratio (PER)	Packet Reception Rate (PRR) (95 % Confidence Intervals - > 1 000 runs)
Runs	tens	500	> 1 000

Annex C: Summary of detect and mitigate parameters

C.1 Detect and mitigate parameters

The following tables summarize the EDCA parameters used in the Detect and Mitigate methods. The values of AIFSN for the RLAN device during mitigation operation are chosen based on the default AIFSN values of the ITS-G5 devices.

Under reduced EDCA mitigation method (10 MHz ITS detection)

Table C.1: EDCA parameters before 10 MHz ITS detection of Reduced EDCA mitigation method

AC	CWmin	CWmax	AIFSN	Max TXOP
Background (AC_BK)	aCWmin = **15**	aCWmax = **1 023**	**7**	**0**
Best Effort (AC_BE)	aCWmin = **15**	aCWmax = **1 023**	**3**	**0**
Video (AC_VI)	((aCWmin + 1) / 2) - 1 = **7**	aCWmin = **15**	**2**	**3,008** ms
Voice (AC_VO)	((aCWmin + 1) / 4) - 1 = **3**	(aCWmin + 1) / 2 - 1 = **7**	**2**	**1,504** ms

Table C.2: EDCA parameters after 10 MHz ITS detection of Reduced EDCA mitigation method

AC	CWmin	CWmax	AIFSN	Max TXOP
Background (AC_BK)	(aCWmin x 2) + 1 = **31**	(aCWmax × 2) + 1 = **2 047**	9 x 2 + (aCWmin × 2) + 1 = **49**	**2,528** ms
Best Effort (AC_BE)	(aCWmin x 2) + 1 = **31**	(aCWmax × 2) + 1 = **2 047**	6 x 2 + (aCWmin × 2) + 1 = **43**	**2,528** ms
Video (AC_VI)	aCWmin = **15**	(aCWmin × 2) + 1 = **31**	3 x 2 + (aCWmin) = **21**	**3,000** ms
Voice (AC_VO)	((aCWmin + 1) / 2) - 1 = **7**	aCWmin = **15**	2 x 2 + ((aCWmin + 1) / 2) - 1 = **11**	**2,080** ms

Under Decreased EDCA Plan A mitigation method (10 MHz ITS detection)

Table C.3: EDCA parameters before 10 MHz ITS detection of Decreased EDCA Plan A mitigation method

AC	**CWmin**	**CWmax**	**AIFSN**	**Max TXOP**
Background (AC_BK)	aCWmin = **15**	aCWmax = **1 023**	**7**	**0**
Best Effort (AC_BE)	aCWmin = **15**	aCWmax = **1 023**	**3**	**0**
Video (AC_VI)	((aCWmin + 1) / 2) - 1 = **7**	aCWmin = **15**	**2**	**3,008** ms
Voice (AC_VO)	((aCWmin + 1) / 4) - 1 = **3**	((aCWmin + 1) / 2) - 1 = **7**	**2**	**1,504** ms

Table C.4: EDCA parameters after 10 MHz ITS detection of Decreased EDCA Plan A mitigation method

AC	CWmin	CWmax	AIFSN	Max TXOP
Background (AC_BK)	aCWmin × 2 + 1= **31**	aCWmax × 2 + 1 = **2 047**	9 x 2 + (aCWmax × 2) + 1 = **2 065**	**2,258** ms
Best Effort (AC_BE)	aCWmin × 2 + 1= **31**	aCWmax × 2 + 1 = **2 047**	6 x 2 + (aCWmax × 2) + 1 = **2 059**	**2,258** ms
Video (AC_VI)	aCWmin = **15**	aCWmin × 2 + 1 = **31**	3 x 2 + aCWmax = **1 029**	**3,008** ms
Voice (AC_VO)	((aCWmin + 1) / 2) - 1 = **7**	aCWmin = **15**	2 x 2 + ((aCWmax + 1) / 2) -1 = **515**	**1,504** ms

Under Decreased EDCA Plan B mitigation method (10 MHz ITS detection)

Table C.5: EDCA parameters before 10 MHz ITS detection of Decreased EDCA Plan B mitigation method

AC	CWmin	CWmax	AIFSN	Max TXOP
Background (AC_BK)	(aCWmin × 2) + 1= **31**	(aCWmax × 2) + 1 = **2 047**	9 × 2 + (aCWmin × 2) + 1 = **49**	**2,258** ms
Best Effort (AC_BE)	(aCWmin × 2) + 1= **31**	(aCWmax × 2) + 1 = **2 047**	6 × 2 + (aCWmin × 2) + 1 = **43**	**2,258** ms
Video (AC_VI)	aCWmin = **15**	(aCWmin × 2) + 1 = **31**	3 × 2 + aCWmin = **21**	**3,008** ms
Voice (AC_VO)	((aCWmin + 1) / 2) - 1 = **7**	aCWmin = **15**	2 × 2 + ((aCWmin + 1) / 2) - 1 = **11**	**1,504** ms

Table C.6: EDCA parameters after 10 MHz ITS detection of Decreased EDCA Plan B mitigation method

AC	CWmin	CWmax	AIFSN	Max TXOP
Background (AC_BK)	(aCWmin × 2) + 1= **31**	(aCWmax × 2) + 1 = **2 047**	9 × 2 + (aCWmax × 2) + 1 = **2 065**	**2,258** ms
Best Effort (AC_BE)	(aCWmin × 2) + 1= **31**	(aCWmax × 2) + 1 = **2 047**	6 × 2 + (aCWmax × 2) + 1 = **2 059**	**2,258** ms
Video (AC_VI)	aCWmin = **15**	(aCWmin × 2) + 1 = **31**	3 × 2 + aCWmax = **1 029**	**3,008** ms
Voice (AC_VO)	((aCWmin + 1) / 2) - 1 = **7**	aCWmin = **15**	2 × 2 + ((aCWmax + 1) / 2) - 1 = **515**	**1,504** ms

Annex D: Summary of regulatory parameters for ITS coexistence techniques proposed in the present document

Table D.1: Regulatory requirement values for detection of ITS (5 855 MHz to 5 905 MHz)

Parameter	Detect and Mitigate (Reduced EDCA)	Detect and Mitigate (Decreased EDCA Plan A)	Detect and Mitigate (Decreased EDCA Plan B)	Detect and Vacate
Parameter settings upon initial move to or boot upon (or wake up on) an ITS channel	Wi-Fi/802.11™ EDCA parameter set.	Wi-Fi/802.11™ EDCA parameter set.	Less aggressive EDCA parameter set.	"Detect and Vacate" methodology as detailed.
ITS-G5 Initial ICCA time (only when initially monitoring the channel (e.g. following a sleep to wake transition)	2 ms	2 ms	2 ms	1 ms
ITS-G5 Detection (Channel Busy)	1 or more ITS-G5 short training symbols detected on any one of four 10 MHz channel detectors CH172, 174, 176, 178 and CH180 within 8 µs. In addition 1 or more 10 MHz short training symbols and two long training symbols detected on any one of channels 172, 174, 176, 178 and 180 within 32 µs.	1 or more ITS-G5 short training symbols detected on any one of four 10 MHz channel detectors CH172, 174, 176, 178 and CH180 within 8 µs. In addition 1 or more 10 MHz short training symbols and two long training symbols detected on any one of channels 172, 174, 176, 178 and 180 within 32 µs.	1 or more ITS-G5 short training symbols detected on any one of four 10 MHz channel detectors CH172, 174, 176, 178 and CH180 within 8 µs. In addition 1 or more 10 MHz short training symbols and two long training symbols detected on any one of channels 172, 174, 176, 178 and 180 within 32 µs.	1 or more ITS-G5 short training symbols detected on any one of four 10 MHz channel detectors CH172, 174, 176, 178 and CH180 within 8 µs. In addition 1 or more 10 MHz short training symbols and two long training symbols detected on any one of channels 172, 174, 176, 178 and 180 within 32 µs.
Action upon ITS-G5 detection	Defer to ITS-G5 Transmission on the RLAN channel where detection occurred. RLAN restricted to single 20 MHz channel on which the detection event occurred. No multi-channel operation for at least 2 s after no detection events.	Defer to ITS-G5 Transmission on the RLAN channel where detection occurred. RLAN restricted to single 20 MHz channel on which the detection event occurred. No multi-channel operation for at least 2 s after no detection events.	Defer to ITS-G5 Transmission on the RLAN channel where detection occurred. RLAN restricted to single 20 MHz channel on which the detection event occurred. No multi-channel operation for at least 2 s after no detection events.	Vacate all RLAN channels that fall within 5 825 MHz to 5 925 MHz for at least [10 s]. An earlier proposal was increased from 2 s during the drafting of the present document.
Extended CCA Time	[200 µs] based upon ITS AIFSN +CWmin ((16 + (3 × 9)) + (15 × 9) = 178 µs)for at least 2 s after detection event.	19 ms ((1 023 × 2) + 1) observation slot times of 9 µs = 18,423 ms, for at least 2 s after detection event.	19 ms ((1 023 × 2) + 1) observation slot times of 9 µs = 18,423 ms, for at least 2 s after detection event.	Not applicable.

Parameter	Detect and Mitigate (Reduced EDCA)	Detect and Mitigate (Decreased EDCA Plan A)	Detect and Mitigate (Decreased EDCA Plan B)	Detect and Vacate
Action after 2 s when ITS transmissions are no longer detected.	May revert to the standard Wi-Fi/802.11™ EDCA parameter set applicable to other non-ITS 5 GHz RLAN channels (e.g. 5 150 MHz to 5 250 MHz, 5 470 MHz to 5 725 MHz bands).	May revert to the EDCA parameter set applicable to other non-ITS 5 GHz RLAN channels (e.g. 5 150 MHz to 5 250 MHz, 5 470 MHz to 5 725 MHz bands).	May revert to a less aggressive EDCA parameter set.	Revert to "Detect and Vacate" methodology as detailed.
ITS-G5 Detection time	≤ 8 µs	≤ 8 µs	≤ 8 µs	≤ 8 µs
Energy Detection time	≤ 8 µs	≤ 8 µs	≤ 8 µs	≤ 8 µs
Initial TXOP Limit (after ICCA)	3 ms	3 ms	3 ms	≤ 200 µs
TXOP Limit	≤ 3 ms	≤ 3 ms	≤ 3 ms	≤ 3 ms
Minimum Idle (TX Back off where TXOP > 2 ms)	≥ (16 + 9) = 25 µs	≥ (16 + 9) = 25 µs	≥ 99 µs	≥ 266 µs. Based upon simulations performed at 266 µs in clause B.3 a level of 300 µs has also been proposed.

Table D.2: ITS-G5 short training symbol detection proposed threshold values

Frequency Band	Detect and Mitigate Value (dBm/10 MHz) (see note 1)	Detect and Vacate Value (dBm/10 MHz) (see notes 1 and 2)
5 855 MHz to 5 895 MHz	-85	-85
5 895 MHz to 5 905 MHz	-85	-65
NOTE 1: This is the level at the input of the receiver of an RLAN device with a maximum e.i.r.p. density of X dBm/10 MHz and assuming a 0 dBi receive antenna. For devices employing different e.i.r.p. spectral density and/or a different receive antenna gain G (dBi) the DFS threshold level at the receiver input follows the following relationship: Detection Threshold (dBm) = -85 + X - e.i.r.p. Spectral Density (dBm/MHz) + G (dBi); however the threshold level should not be lower than Y dBm assuming a 0 dBi receive antenna gain. NOTE 2: This is the level at the input of the receiver of an RLAN device with a maximum e.i.r.p. density of X dBm/10 MHz and assuming a 0 dBi receive antenna. For devices employing different e.i.r.p. spectral density and/or a different receive antenna gain G (dBi) the DFS threshold level at the receiver input follows the following relationship: Detection Threshold (dBm) = -65 + X - e.i.r.p. Spectral Density (dBm/MHz) + G (dBi); however the threshold level should not be lower than Y dBm assuming a 0 dBi receive antenna gain.		

Table D.3: Energy detection proposed threshold values

Frequency Band	Detect and Mitigate Value (dBm/10 MHz) (see note)	Detect and Vacate Value (dBm/10 MHz) (see note)
5 855 MHz to 5 905 MHz	-65	-65
NOTE: This is the level at the input of the receiver of an RLAN device with a maximum e.i.r.p. density of X dBm/10 MHz and assuming a 0 dBi receive antenna. For devices employing different e.i.r.p. spectral density and/or a different receive antenna gain G (dBi) the DFS threshold level at the receiver input follows the following relationship: Detection Threshold (dBm) = -65 + X - e.i.r.p. Spectral Density (dBm/MHz) + G (dBi); however the threshold level should not be lower than Y dBm assuming a 0 dBi receive antenna gain.		

History

Document history		
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