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TECHNICAL REPORT

Intelligent Transport Systems (ITS);
Study on receiver requirements in ETSI EN 302 571

Reference

DTR/ERM-TG37-275

Keywords

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Foreword

This Technical Report (TR) has been produced by ETSI Technical Committee Electromagnetic compatibility and Radio spectrum Matters (ERM).

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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1 Scope

1.1 Rationale for the present document

The rationale for the present document is twofold.

Firstly, the initiative to study the possibility to include improved receiving parameters such as selectivity and sensitivity in future releases of ETSI EN 302 571 [i.1] is based on recommendations given in ETSI EG 203 336 [i.5].

Secondly, the Harmonised Standard ETSI EN 302 571 [i.1] was first published when only a single technology was considered for Cooperative ITS communication.. Reformulation of (some of) the requirements defined in ETSI EN 302 571 [i.1] in a technology neutral manner is therefore strongly desirable, to address the various technologies existing today, and also future technologies.

Therefore, a new technical study item was proposed and approved: DTR/ERM-TG37-275, resulting in the present document.

1.2 Need for receiver performance requirements

The intention of article 3.2 of Directive 2014/53/EU [i.7] in relation to a receiver is explained in recitals 10 and 11 of the Directive, which states:

"...in the case of a receiver, it has a level of performance that allows it to operate as intended and protects it against the risk of harmful interference, in particular from shared or adjacent channels, and, in so doing, supports improvements in the efficient use of shared or adjacent channels.

Although receivers do not themselves cause harmful interference, reception capabilities are an increasingly important factor in ensuring the efficient use of radio spectrum by way of an increased resilience of receivers against harmful interference and unwanted signals on the basis of the relevant essential requirements of Union harmonization legislation."

1.3 Scope of the present document

The scope of the present document is to review requirements on the receiver sensitivity, adjacent channel rejection and the alternate adjacent channel rejection (hereafter referred to as "receiver requirements") as defined in ETSI EN 302 571 [i.1] with the aim:

- To analyse those receiver requirement limits and investigate if it is possible to tighten them, taking state-of-the-art technologies into account.
- To assess the feasibility of defining such receiver requirements and associated tests for demonstrating compliance in a technology neutral manner.
- If not feasible, to specify alternative receiver requirements and associated tests for demonstrating compliance.

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, they assist the user with regard to a particular subject area.

[i.1] ETSI EN 302 571 (V2.1.1): "Intelligent Transport Systems (ITS); Radiocommunications equipment operating in the 5 855 MHz to 5 925 MHz frequency band; Harmonised Standard covering the essential requirements of article 3.2 of Directive 2014/53/EU".

[i.2] ETSI EN 302 663 (V1.3.1): "Intelligent Transport Systems (ITS); ITS-G5 Access layer specification for Intelligent Transport Systems operating in the 5 GHz frequency band".

[i.3] IEEE 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.4] ETSI TS 136 101 (V14.21.0): "LTE; Evolved Universal Terrestrial Radio Access (E-UTRA); User Equipment (UE) radio transmission and reception (3GPP TS 36.101 version 14.21.0 Release 14)".

[i.5] ETSI EG 203 336 (V1.2.1): "Guide for the selection of technical parameters for the production of Harmonised Standards covering article 3.1(b) and article 3.2 of Directive 2014/53/EU".

[i.6] 3GPP TR 36.786 (V14.0.0): "Vehicle-to-Everything (V2X) services based on LTE; User Equipment (UE) radio transmission and reception".

[i.7] Directive 2014/53/EU of the European Parliament and of the Council of 16 April 2014 on the harmonisation of the laws of the Member States relating to the making available on the market of radio equipment and repealing Directive 1999/5/EC, (OJ L153, 22.5.2014, p62).

[i.8] Massachusetts Institute of Technology lecture notes: "Principles of Digital Communication II".

NOTE: Available at https://ocw.mit.edu/courses/electrical-engineering-and-computer-science/6-451-principles-of-digital-communication-ii-spring-2005/readings-and-lecture-notes/MIT6_451S05_FullLecNotes.pdf.

[i.9] John G. Proakis: "Digital Communications", McGraw-Hill International Edition, 4th Edition, 2001.

[i.10] ETSI TS 138 101-1 (V16.7.0): "5G; NR; User Equipment (UE) radio transmission and reception; Part 1: Range 1 Standalone (3GPP TS 38.101-1 version 16.7.0 Release 16)".

[i.11] ETSI TS 136 521-1 (V14.6.0): "LTE; Evolved Universal Terrestrial Radio Access (E-UTRA); User Equipment (UE) conformance specification; Radio transmission and reception; Part 1: Conformance testing (3GPP TS 36.521-1 version 14.6.0 Release 14)".

[i.12] 3GPP TR 36.785: "Vehicle to Vehicle (V2V) services based on LTE sidelink; User Equipment (UE) radio transmission and reception".

[i.13] ETSI EN 300 328 (V2.2.2): "Wideband transmission systems; Data transmission equipment operating in the 2,4 GHz band; Harmonised Standard for access to radio spectrum".

3 Definition of terms, symbols and abbreviations

3.1 Terms

Void.

3.2 Symbols

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

K_B	Boltzmann constant
L_{CRB}	Sidelink allocated RB size
N_{RB}	Number of Resource Blocks
N_C	Number of OFDM data subcarriers
$P_{E\ QAM}$	QAM symbol error probability
P_I	Power of the Interferer
$P_{S\ dBm}$	Receiver sensitivity
R_{MCS}	Nominal data rate depending on MCS

3.3 Abbreviations

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

3GPP	3rd Generation Partnership Project
5G	5th generation of cellular mobile communications
AACR	Alternate Adjacent Channel Rejection
AACS	Alternate Adjacent Channel Selectivity
AC	Access Category
AC_BE	Access Category Best Effort
ACR	Adjacent Channel Rejection
ACS	Adjacent Channel Selectivity
AIFS	Arbitration InterFrame Space
AT	Access Terminal
AWGN	Additive White Gaussian Noise
BLER	BLock Error Rate
BPSK	Binary Phase Shift Keying
BW	Bandwidth
CAM	Cooperative Awareness Message
CR	Coding Rate
CRC	Cyclic Redundance Check
CW	Continuous Wave
DG GROW	Directorate General for Internal Market, Industry, Entrepreneurship and Small and medium-sized enterprises (of the European Commission)
DUT	Device Under Test
GNSS	Global Navigation Satellite System
HARQ	Hybrid Automatic Repeat Request
HD	Half Duplex
IM	Implementation Margin
ITS	Intelligent Transport Systems
ITS-G5	Access layer technology

NOTE: As defined in ETSI EN 302 663 [i.2].

LTE	Long Term Evolution
MAC	Media Access Control
MCS	Modulation and Coding Scheme
MMI	Man Machine Interface
NC	Number of (sub)Carriers

NF	Noise Figure
NR	New Radio
NR-V2X	New Radio Vehicle-to-Everything
OFDM	Orthogonal Frequency Division Multiplexing
PC5	Interface between the ITS stations used for V2X sidelink communication
PE	Probability of Error
PER	Packet Error Rate
PHY	PHYsical layer
PRR	Packet Reception Ratio
PS	Sensitivity Power
PSCCH	Physical Sidelink Control CHannel
PSDU	PLCP Service Data Unit
PSK	Phase Shift Keying
PSSCH	Physical Sidelink Shared CHannel
PUSCH	Physical Uplink Shared Channel
QAM	Quadrature Amplitude Modulation
QPSK	Quadrate Phase Shift Keying
RB	Resource Block
RMC	Reference Measurement Channel
RS	Reference Symbol
RX	Radio receiver
SA	Spectrum Analyser
SCI	Sidelink Control Information
SCS	SubCarrier Spacing
SER	Symbol Error Rate
SL	SideLink
SNR	Signal to Noise Ratio
S-SSB	Sidelink Synchronization Signal Block
SS	System Simulator
STA	Station
TBS	Transport Block Size
TDD	Time Division Duplex
TH	Temperature High
TL	Temperature Low
TS	Technical Specification
TX	Radio transmitter
UE	(3GPP) User Equipment
UTC	Coordinated Universal Time
VH	Higher extreme Voltage
VL	Lower extreme Voltage
V2V	Vehicle to Vehicle
V2X	Vehicle-to-Everything

4 Study on definitions used in reference documents

4.1 Introduction

This clause intends to clarify definitions of key technical terms used in the present document. Firstly, definitions from several reference documents are recalled. Secondly, proposal definitions for use in the present document are detailed.

4.2 Existing definitions in reference documents

4.2.1 Definitions in ETSI EN 302 571

The following italic text shows the definitions taken from ETSI EN 302 571 [i.1]. These definitions are to be understood with the partitioning of the band into 7 channels of 10 MHz: the frequency offsets mentioned are relative to this organization and are not generically transposable to other channel bandwidths. Also, it should be noted that the ± 50 MHz blocking offset may fall in-band, since the ITS band is 70 MHz wide. Regarding receiver sensitivity, the assumed noise margins may have to be checked if still valid.

*"**Receiver selectivity** is a measure of the receiver's ability to discriminate between wanted signal to which the receiver is tuned to and unwanted signals stemming from other frequency bands. Receiver selectivity herein is comprised of:*

i) adjacent channel rejection;

ii) alternate channel rejection; and

iii) blocking.

The adjacent channel rejection is a measure of the capability of the receiver to operate satisfactorily in the presence of a signal in the adjacent channel, which differs in frequency from the wanted signal by ± 10 MHz.

The alternate channel rejection is a measure of the capability of the receiver to operate satisfactorily in the presence of a signal in the alternate adjacent channel, which differs in frequency from the wanted signal by ± 20 MHz.

***Blocking** is a measure of the capability of the receiver to operate satisfactorily in the presence of a signal in frequency band further away and it shall be tested at ± 50 MHz, ± 100 MHz, and ± 200 MHz. Blocking testing shall be performed at least at 6 different frequency offset positions. The manufacturer of the equipment can add additional frequency offsets positions.*

***Receiver sensitivity** is defined as the minimum receive signal level at the antenna connector required for a given error rate, coding rate and modulation scheme (noise factor of 10 dB and 5 dB implementation margins are assumed). The sensitivity test shall be performed with a single antenna transmitter. The manufacturer of the equipment may use one or several receiver antennas. The sensitivity tests shall be performed without message retransmissions."*

4.2.2 Definitions in ETSI EG 203 336

The following italic text shows the definitions taken from ETSI EG 203 336 [i.5]. These definitions may be more generic, potentially covering for any channel bandwidth. The receiver selectivity definition is maybe less straightforward, pointing to single signal & multiple response rejection selectivity components.

*"**adjacent channels:** channel offset from the wanted channel by the channel spacing*

***alternate channels:** channel(s) offset from the wanted channel by twice the channel spacing*

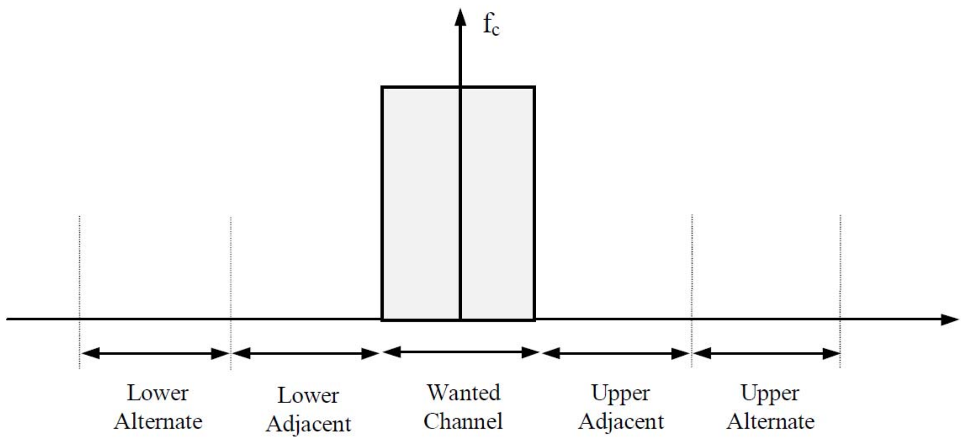

Figure 1: Adjacent and alternate channel definitions (picture from ETSI EG 203 336 [i.5])

***Receiver selectivity** is described in Recommendation ITU-R SM.332-4 [19] identifying the capability to receive a wanted signal, without exceeding a given degradation, due to the presence of an unwanted signal which differs in frequency from the wanted signal by a specified amount. Recommendation ITU-R SM.332-4 [19] makes a distinction between single signal selectivity and multiple signal selectivity.*

***Single signal selectivity** refers to effects measured within the linear range of the receiver. For the purposes of the present document these are:*

- *attenuation slope; and*
- *spurious response rejection.*

Attenuation slope is a parameter that was mainly applicable to historic systems using analogue modulation; an acceptable alternative in a Harmonised Standard is to specify adjacent signal (or channel) selectivity.

Spurious response rejection includes all possible spurious responses of the receiver but Recommendation ITU-R SM.332-4 [19] specifically identifies image-rejection ratio and intermediate-frequency rejection ratio. Receivers with multiple intermediate-frequencies will have image responses and intermediate-frequency responses for each intermediate-frequency.

***Multiple response rejection selectivity** is considered as effective selectivity which includes blocking, adjacent-signal (adjacent-channel), selectivity and radio-frequency intermodulation."*

4.2.3 Definitions in LTE-V2X ETSI TS 136 101

The following italic text shows the definitions used in ETSI TS 136 101 [i.4].

***"Adjacent Channel Selectivity (ACS)** is a measure of a receiver's ability to receive a E-UTRA signal at its assigned channel frequency in the presence of an adjacent channel signal at a given frequency offset from the centre frequency of the assigned channel. ACS is the ratio of the receive filter attenuation on the assigned channel frequency to the receive filter attenuation on the adjacent channel(s).*

***(7.3) The reference sensitivity power level REFSENS** is the minimum mean power applied to each one of the UE antenna ports for all UE categories except category 0, category M1, category M2, and category 1bis, or to the single antenna port for UE category 0, UE category M1, category M2, and UE category 1bis, at which the throughput shall meet or exceed the requirements for the specified reference measurement channel.*

(7.3.1G) Minimum requirements (QPSK) for V2X. When UE is configured for E-UTRA V2X reception non-concurrent with E-UTRA uplink transmissions for E-UTRA V2X operating bands specified in Table 5.5G-1, the throughput shall be ≥ 95% of the maximum throughput of the reference measurement channels.

***In-band blocking** is defined for an unwanted interfering signal falling into the UE receive band or into the first 15 MHz below or above the UE receive band at which the relative throughput shall meet or exceed the minimum requirement for the specified measurement channels."*

NOTE: As further elaborated in clause 6.1.3, in-band blocking with 'case1' offsets corresponds to a similar test as the IEEE Alternate Adjacent Channel Rejection described in [i.3].

4.2.4 Relationship between ACS and ACR

It should be noted that the ACR definition used in IEEE 802.11 [i.3] or ETSI EN 302 571 [i.1] differs from the ACS definition from 3GPP. A detailed comparison is provided in clause B.4.

4.2.5 Sensitivity vs required throughput

It is possible to derive an empirical relationship between the receiver sensitivity level and the SNR required for a given throughput based on the noise figure and implementation margin. Corresponding analysis is provided in Annex F.

4.3 Definitions for use in the present document

This clause contains definitions for use in the present document. This clause does not propose any modification of the ITS band channelization. All the definitions from ETSI EN 302 571 [i.1] do apply, except for the terms which are defined in the present clause and which overrule the definitions from ETSI EN 302 571 [i.1]. Modifications are proposed for definitions of adjacent channel rejection and alternate channel rejection in an attempt to make them more generic, as in ETSI EG 203 336 [i.5], in case of change of channel bandwidth in the future. The receiver sensitivity definition is updated to match the outcome of the present study (see details in clause 5.3).

The **adjacent channel rejection** is a measure of the capability of the receiver to operate satisfactorily in the presence of a signal in the lower or upper adjacent channel, which differs in frequency from the wanted signal by ± the channel spacing (e.g. ±10 MHz for 10 MHz channel spacing, ±20 MHz for 20 MHz channel spacing, etc.).

The **alternate channel rejection** is a measure of the capability of the receiver to operate satisfactorily in the presence of a signal in the lower or upper alternate adjacent channel, which differs in frequency from the wanted signal by ± double the channel spacing (e.g. ±20 MHz for 10 MHz channel spacing, ±40 MHz for 20 MHz channel spacing, etc.).

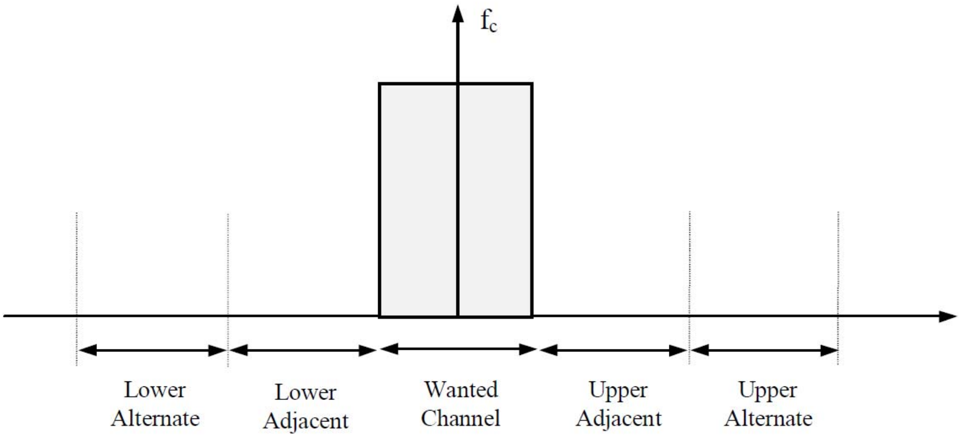

Figure 2: Adjacent and alternate channel definitions

Receiver sensitivity is defined as the minimum receive signal level at the antenna connector required for a given packet error rate and effective data-rate. The sensitivity test should be performed with a single antenna transmitter. The manufacturer of the equipment may use one or several receiver antennas. The sensitivity test should be performed without message retransmissions.

5 Study on receiver sensitivity requirements

5.1 Requirements as published in reference documents

5.1.1 Requirements in IEEE 802.11

IEEE Std 802.11-2016 [i.3] clause 17.3.10.2 defines sensitivity requirements based on 10 % PER and packets of 1 000 bytes. The minimum sensitivity levels are defined for each modulation and coding scheme, for 5, 10 and 20 MHz channel bandwidth (for example -82 dBm for QPSK ½ for 10 MHz channel) as per [i.3] Table 17-18, assuming 10 dB noise factor and 5 dB implementation margin, as shown in Table 1.

Table 1: Limits for receiver sensitivity as specified by IEEE 802.11-2016 [i.3] for 10 MHz channel

Modulation	Coding rate	Minimum sensitivity (dBm)
BPSK	1/2	-85
BPSK	3/4	-84
QPSK	1/2	-82
QPSK	3/4	-80
16-QAM	1/2	-77
16-QAM	3/4	-73
64-QAM	2/3	-69
64-QAM	3/4	-68

NOTE: It should be noted that the IEEE 802.11-2016 [i.3] access layer is often referred to as IEEE 802.11p, which is its older name, and the letter 'p' refers to an amendment in earlier versions of the IEEE 802.11 standard.

5.1.2 Requirements in ETSI EN 302 571

The minimum sensitivity requirements defined in the published ETSI EN 302 571 [i.1] are instructed in clause 4.2.8.2, as shown in the below italic text:

"The receiver sensitivity shall be less or equal to the values given in Table 9 for a packet error rate (PER) of 10-1 for 1 000 octet frames assuming stationary, non-fading channel conditions.

Table 9: Receiver sensitivity

Modulation	*Coding rate*	*Minimum sensitivity for 10 MHz channel spacing (dBm)*
BPSK	*1/2*	*-85*
BPSK	*3/4*	*-84*
QPSK	*1/2*	*-82*
QPSK	*3/4*	*-80*
16-QAM	*1/2*	*-77*
16-QAM	*3/4*	*-73*
64-QAM	*2/3*	*-69*
64-QAM	*3/4*	*-68*

NOTE: Limits apply only to the applicable modulations to the DUT."

Observations:

- Requirements are expressed in form PER ≤ 10 %.
- Requirements are expressed per ITS-G5 transmit rate (e.g. modulation coding scheme).
- Requirements are thus not expressed in a technology generic way, being only applicable to IEEE 802.11-2016 [i.3].
- The values specified for sensitivity requirements are identical as the ones indicated in table 17-18 of IEEE 802.11-2016 [i.3], for 10 MHz channel.
- Test procedure is identical to the one taught by IEEE 802.11-2016 [i.3] in clauses 17.3.10.2 (1 000 octets frame, etc.).
- The test assumes only cabled environment (non-fading) conditions (sometimes referred to as "clean channel").

5.1.3 Requirements in 3GPP LTE Release-14

ETSI TS 136 101 [i.4] defines LTE Release14 User Equipment (UE) radio transmission and reception minimum performance requirements:

- Clause 14 "Performance requirement (V2X Sidelink Communication)" addresses Sidelink V2X direct communication (mode 4) demodulation performance requirements. But these are not directly applicable to the context of an EN (for example PSSCH and PSCCH are tested separately, etc.).
- Clause 7.3.1 "Reference sensitivity power level" addresses Sidelink V2X direct communication (mode 4) sensitivity requirements, in subclause 7.3.1G "Minimum requirements (QPSK) for V2X", as shown with the below italic text:

"When UE is configured for E-UTRA V2X reception non-concurrent with E-UTRA uplink transmissions for E-UTRA V2X operating bands specified in Table 5.5G-1, the throughput shall be ≥ 95% of the maximum throughput of the reference measurement channels as specified in Annexes A.8.2 with parameters specified in Table 7.3.1G-1.

Table 7.3.1G-1: Reference sensitivity of E-UTRA V2X Bands (PC5)

Channel bandwidth							
E-UTRA V2X Band	*1.4 MHz (dBm)*	*3 MHz (dBm)*	*5 MHz (dBm)*	*10 MHz (dBm)*	*15 MHz (dBm)*	*20 MHz (dBm)*	*Duplex Mode*
47				*-90.4*		*-87.5*	*HD*
NOTE 1: Reference measurement channel is defined in A.8.2. NOTE 2: The signal power is specified per port.							

"

ETSI TS 136 521-1 [i.11], clause 7.3G "Reference sensitivity level for V2X Communication" contains additional information:

- Clause 7.3G.0 "Minimum conformance requirements" provides identical description with identical parameterization. The difference between ETSI TS 136 101 [i.4] and ETSI TS 136 521-1 [i.11] is that the former defines the requirements as "minimum performance requirement" while the latter defines the requirements as "minimum conformance requirement".
- Clause 7.3G.1 "Reference sensitivity level for V2X Communication/Non-concurrent with E-UTRA uplink transmissions" provides test procedure details.

An extract of ETSI TS 136 521-1 [i.11] clause 7.3G "Reference sensitivity level for V2X Communication" is provided in Annex D.

Observations:

- Requirements are expressed in form of throughput to be ≥ 95 % of the maximum throughput of the reference measurement channel A.8.2 (corresponds to PER ≤ 5 %).
- There is only one requirement per channel bandwidth, for a configuration (A.8.2) that is QPSK with coding rate of approximately 1/3.

5.1.4 Requirements in IEEE 802.11bd

The sensitivity requirements defined in IEEE 802.11bd (still under development) will most likely be identical to the ones from IEEE 802.11-2016 [i.3] for the Modulation and Coding Scheme (MCS) that overlap between IEEE 802.11p and IEEE 802.11bd.

5.1.5 Requirements in 3GPP 5G NR V2X

ETSI TS 138 101-1 [i.10] defines NR V2X User Equipment (UE) radio transmission and reception minimum performance requirements. Clause 7.3E Reference defines sensitivity for V2X, as shown with the below italic table. Band n47 indicates the 5,9 GHz ITS band.

"Table 7.3E.2-1: Reference sensitivity of NR V2X Bands (PC5)

		Channel bandwidth / PREFSENS_V2X(dBm)				
NR V2X Band	***SCS kHz***	***10 MHz***	***20 MHz***	***30 MHz***	***40 MHz***	***Duplex Mode***
n38	*15*	*-96.5*	*-93.2*	*-91.4*	*-90.1*	*HD*
	30	*-96.1*	*-93.4*	*-91.7*	*-90.2*	*HD*
	60	*-96.9*	*-93.1*	*-91.9*	*-90.4*	*HD*
n47	*15*	*-92.5*	*-89.2*	*-87.4*	*-86.1*	*HD*
	30	*-92.1*	*-89.4*	*-87.7*	*-86.2*	*HD*
	60	*-92.9*	*-89.1*	*-87.9*	*-86.4*	*HD*
NOTE 1: Reference measurement channel is defined in A.8. NOTE 2: The signal power is specified per antenna port. NOTE 3: Void.						

"

The Sidelink TX configuration for reference sensitivity tests is described in the below italic text.

"Table 7.3E.2-2: Sidelink TX configuration for reference sensitivity of NR V2X Bands (PC5)

NR Band / SCS / Channel bandwidth / Duplex mode						
NR V2X Band	***SCS kHz***	***10 MHz***	***20 MHz***	***30 MHz***	***40 MHz***	***Duplex Mode***
n38	***15***	***50***	***105***	***160***	***216***	***HD***
	30	***24***	***50***	***75***	***105***	***HD***
	60	***10[2]***	***24***	***36***	***50***	***HD***
n47	*15*	*50*	*105*	*160*	*216*	*HD*
	30	*24*	*50*	*75*	*105*	*HD*
	60	*10[2]*	*24*	*36*	*50*	*HD*
NOTE 1: The sidelink allocated RB (LCRB) size could be adjusted according to resource pool configuration in [7]. NOTE 2: For the case, 11 RB is allowed for S-SSB Block.						

"

Observations:

- The sensitivity requirements values defined in 5G NR V2X are different from the ones defined in LTE-V2X by 2,5 dB at most.
- The Sidelink TX configuration for reference sensitivity tests are similar as they occupy all available RB.

Table 2: Comparison of LTE-V2X and 5G NR V2X receiver sensitivity requirements for 10 MHz channel in 5,9 GHz ITS band

Standard & configuration	Minimum sensitivity for 10 MHz channel spacing (dBm)
LTE-V2X	-90,4
5G NR V2X, 15 kHz SCS	-92,5
5G NR V2X, 30 kHz SCS	-92,1
5G NR V2X, 60 kHz SCS	-92,9

5.2 Comparison of ITS-G5 and LTE-V2X sensitivity values

This clause compares the sensitivity requirements as expressed for ITS-G5 and LTE-V2X, as well as with the theoretical values obtained from the generic sensitivity limit function from clause F.4.2.

LTE-V2X and ITS-G5 protocols have significant differences in their modulation and coding schemes, channel access mechanisms, time frequency organization of the packet, as well as in the sensitivity test procedures. These differences prevent performing a direct comparison of the sensitivity values.

A new generic term 'effective data rate' $\bar{R}_{eff\,Tx}$ is proposed, and can be applied to any wireless protocol, assuming a constant PER. Further technical details are available in clause F.4.2. $\bar{R}_{eff\,Tx}$ is obtained from the nominal data rate *RMCS* (which unit is $MBit/s$), the management time overhead t_m, the packet duration t_p and the packet error rate limit PER set to 10 % according to Equation (5.2.1):

$$\bar{R}_{\text{eff Tx}} = R_{MCS} \times (1 - PER) \times \frac{t_p - t_m}{t_p} \qquad (5.2.1)$$

For ITS-G5, applicability of Equation (5.2.1) is straight forward since the nominal data rate *RMCS*, the management time overhead t_m and the packet duration t_p are available. The $\bar{R}_{\text{eff Tx}}$ for LTE-V2X can be translated to Equation (5.2.2):

$$\bar{R}_{\text{eff Tx}} = \frac{TBS_{MCS}}{1\,000} \times (1 - PER) \left[\frac{MBit}{s}\right] \qquad (5.2.2)$$

Where TBS is the LTE Transport Block Size (TBS) in bits, which is defined depending on the Modulation and Coding Scheme (MCS).

Furthermore, as shown in clause F.4.3.5, the ITS-G5 and LTE-V2X sensitivity values can be compared to a generic receiver sensitivity limit. The equation of the generic receiver sensitivity limit is:

$$P_{GSens} = 10\log_{10}\left(2^{\frac{\bar{R}_{\text{eff Tx}}}{4}\frac{1}{[MBit/s]}} - 1\right) - 81{,}3\,dB \qquad (5.2.3)$$

Figure 3 and Figure 4 provide a comparison of IEEE 802.11-2016 [i.3] (or ITS-G5) and LTE-V2X sensitivity from clauses 5.1.1 and 5.1.3, respectively, with the proposed generic sensitivity limit Equation (5.2.3). It can be noted that the markers in Figure 3 and Figure 4 are similar, but not identical, as the effective data rates are slightly different. The shape of the markers relates to the modulation and the colour to the coding rate.

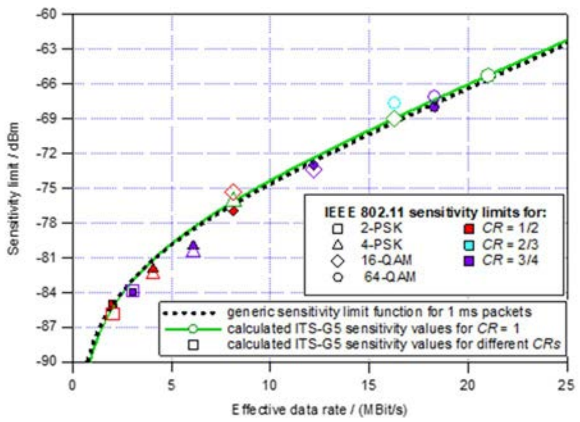

Figure 3: Comparison of calculated ITS-G5 sensitivity values with the proposed generic sensitivity limit and with the limits from IEEE 802.11-2016 [i.3]

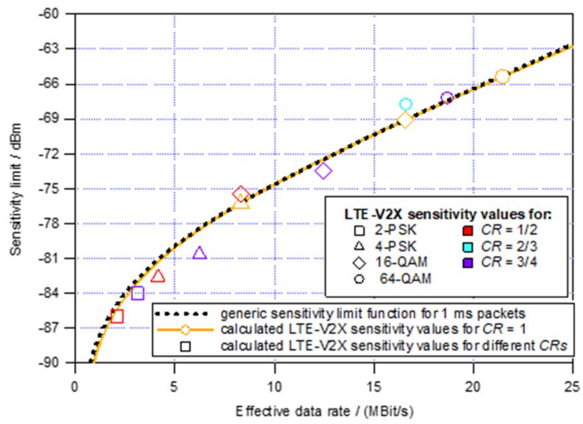

Figure 4: Comparison of calculated LTE-V2X sensitivity values with the proposed generic sensitivity limit

It can be observed that both ITS-G5 and LTE-V2X sensitivity limits follow very closely the generic sensitivity limit function Equation (5.2.3). Thus, ITS-G5 and LTE-V2X sensitivity limits requirements as expressed in their respective standards are well aligned. In summary, the generic sensitivity limit function Equation (5.2.3) could be used to define the sensitivity limits requirements in a generic way, and can be applied to any technology as it is only dependent on the effective data rate.

5.3 Recommendations for receiver sensitivity test

It is proposed that the term effective data rate $\bar{R}_{eff\,Tx}$ is used as a generic way to define the effective throughput, applicable to ITS-G5, LTE-V2X and future protocols regardless of their packet structure and packet sizes used for testing. Also, it is proposed that technologies that can adjust packet duration set it to be as close as possible to 1 ms, and technologies that have fixed packet size use multiple subframes to get to as close as possible to 1 ms, including management overhead as defined for example in clause F.4.3.2.

It is proposed that the equation of the generic receiver sensitivity limit Equation (5.2.3) is modified to form Equation (5.3.1) of the receiver sensitivity requirement to be used for testing sensitivity in the present document:

$$P_{Sens} = \left\lfloor 10 \log_{10}\left(2^{\frac{\bar{R}_{\mathrm{eff\,Tx}}}{4}\frac{1}{[MBit/s]}} - 1\right) - 83{,}8\,dB \right\rfloor \quad (5.3.1)$$

Compared to Equation (5.2.3), it can be noted that Equation (5.3.1) is 3 dB more stringent to reflect a reduction in the implementation margin from 12 to 9 dB. It also includes a rounding operation to ensure integer values only for the sensitivity requirement (the rounding is realized adding $+\frac{1}{2}$ and using the flooring operator '$\lfloor \quad \rfloor$'). 12 dB implementation margin has been assumed for deriving Equation (5.2.3), while 9 dB of implementation margin is thought to be aligned with capability of recent available equipment. It should be noted that further lowering the sensitivity is not foreseen to be possible in the future as it would be getting too close to the theoretical limits.

The proposed data-rate test-points are described in Table 3 and Table 4. The associated sensitivity limit is obtained from Equation (5.3.1). One way of testing is to test three test-points, as described in example 1 and in Table 3. Another way of testing is to have only one test-point, as described in example 2 and in Table 4.

EXAMPLE 1: Three test-points, as shown in Table 3, are defined as having an effective data rate R_{eff} < 3,5 MBit/s, 3,5 MBit/s to 4,5 MBit/s and > 4,5 MBit/s respectively. This option stems from the sensitivity limit functions (5.2.3) and (5.3.1) which have the shape of a straight line after an initial bend at the lower rates (below 4,5 MBits/s). The three test-points aim at capturing a lower bound average effective data rate, a typical data-rate and an upper-bound data-rate (ideally the highest operational effective data rate of the DUT for test point).

Table 3: Proposal for testing sensitivity with multiple data-rate test points

$\bar{R}_{eff\,Tx}$
< 3,5 MBit/s
3,5 MBit/s to 4,5 MBit/s
> 4,5 MBit/s

EXAMPLE 2: One test-point, as shown in Table 4, is defined as having an effective data rate R_{eff} < 4,5 MBit/s. This option promotes only one test-point as Doppler and fading effects, which are dominating at higher MCS values, are not considered in such a test setup.

Table 4: Proposal for testing sensitivity with single data-rate test point

$\bar{R}_{eff\,Tx}$
< 4,5 MBit/s

The proposed test procedure for each data-rate test point is provided in clause F.4.2.

5.4 Example derivation of data-rate test points

5.4.1 Derived data-rate test points and sensitivity limits for ITS-G5

Table 5 provides sensitivity values for ITS-G5 using Equation (5.3.1), see column "New sensitivity limit", given test-points outlined in example 1 and Table 3. Further, Table 5 tabulates all possible MCS for ITS-G5 together with the sensitivity values stemming from ETSI EN 302 571 [i.1] (column "Old sensitivity limits") defined for 1 000 bytes packets. It should be noted that for certain data-rate test points from Table 3, several MCS may be used. Packet duration is set to 1 ms, including management overhead as defined in clause F.4.2.

Table 5: Receiver sensitivity requirements following definitions from example 1 and Table 3

$\bar{R}_{eff\,Tx}$ range	MCS	Nominal data rate (MBit/s)	Packet size (bytes)	$\bar{R}_{eff\,Tx}$ (MBit/s)	New sensitivity limit (dBm)	Old sensitivity limit (dBm)
< 3,5 MBit/s	MCS 0 (BPSK ½)	3,0	279	2,0	-88	-85
	MCS 1 (BPSK ¾)	4,5	420	3,0	-86	-84
3,5 MBit/s to 4,5 MBit/s	MCS 2 (QPSK ½)	6,0	561	4,1	-84	-82
> 4,5 MBit/s	MCS 3 (QPSK ¾)	9,0	843	6,1	-82	-80
	MCS 4 (16-QAM ½)	12,0	1 125	8,1	-79	-77
	MCS 5 (16-QAM ¾)	18	1 689	12,2	-76	-73
	MCS 6 (64-QAM 2/3)	24	2 253	16,3	-72	-69
	MCS 7 (64-QAM ¾)	27	2 535	18,3	-71	-68
NOTE: "New sensitivity limits" refers to the test procedure and requirements as described in the present document. "Old sensitivity limits" refers to the test procedure and requirements described in ETSI EN 302 571 [i.1], which defines 1 000 bytes packets, and is thus only related to MCS column of this table. This column is provided only for information and cannot be compared directly to the 'New' requirements values.						

Table 6 provides sensitivity values for ITS-G5 using Equation (5.3.1), see column "New sensitivity limit", given test-points outlined in example 2 and Table 4.

Table 6: Receiver sensitivity requirements following definitions from example 2 and Table 4

$\bar{R}_{eff\,Tx}$ range	MCS	Nominal data rate (MBit/s)	Packet size (bytes)	$\bar{R}_{eff\,Tx}$ (MBit/s)	New sensitivity limit (dBm)	Old sensitivity limit (dBm)
< 4,5 MBit/s	MCS 0 (BPSK ½)	3,0	279	2,0	-88	-85
	MCS 1 (BPSK ¾)	4,5	420	3,0	-86	-84
	MCS 2 (QPSK ½)	6,0	561	4,1	-84	-82
NOTE: "New sensitivity limits" refers to the test procedure and requirements as described in the present document. "Old sensitivity limits" refers to the test procedure and requirements described in ETSI EN 302 571 [i.1], which defines 1 000 bytes packets, and is thus only related to MCS column of this table. This column is provided only for information and cannot be compared directly to the 'New' requirements values.						

5.4.2 Comparison between the "old" and "new" sensitivity limits for ITS-G5

As highlighted in the NOTE entries of Table 5 and Table 6, the "New sensitivity limit" requirements are derived using Equation (5.3.1) assuming 1 ms packet duration, while the "Old sensitivity limits" originate from ETSI EN 302 571 [i.1] defined for 1 000 bytes packets.

Figure 5 provides a comparison of the "old" and "new" sensitivity limits for ITS-G5. The blue triangle-shape markers depict the "Old sensitivity limits" from ETSI EN 302 571 [i.1] defined for 1 000 bytes packets. The blue dotted line is a linear fitting of the blue triangle-shape markers. The green line depicts the "New sensitivity limit" requirements derived using Equation (5.3.1) assuming 1 ms packet duration. The black square-shape markers show application of the Equation (5.3.1) for ITS-G5 MCS (not all such entries needed to be tested, according to example 1 and Table 3 or according to example 2 and Table 4.

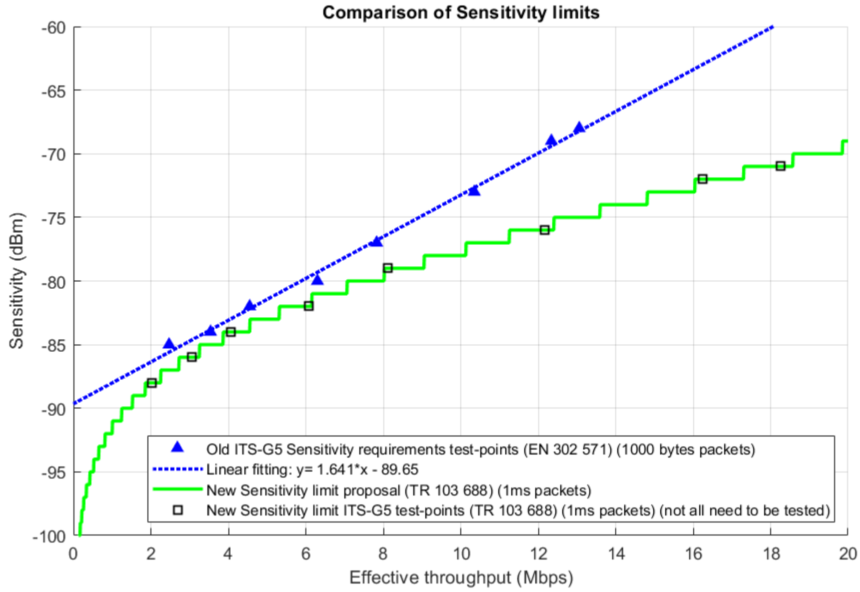

Figure 5: Comparison of the "old" and "new" sensitivity limits for ITS-G5

5.4.3 Derived data-rate test points and sensitivity limits for LTE-V2X

Table 7 provides sensitivity values for LTE-V2X using Equation (5.3.1), see column "New sensitivity limit", given the test-points outlined in example 1 and Table 3. It is assumed that LTE packet occupies all subchannels and that the MCS range 0-11 is available.

Table 7: Receiver sensitivity requirements following definitions from example 1 and Table 3

$\bar{R}_{eff\,Tx}$ range	I_MCS	Transport Block size (bits)	$\bar{R}_{eff\,Tx}$ (MBit/s)	New Sensitivity limit (dBm)
< 3,5 MBit/s	3	2 792	2,51	-87
	4	3 496	3,15	-86
3,5 MBit/s to 4,5 MBit/s	5	4 264	3,84	-85
	6	4 968	4,47	-84
> 4,5 MBit/s	7	5 992	5,39	-82
	8	6 712	6,04	-82
	9	7 480	6,73	-81
	10	8 504	7,65	-80
	11	8 504	7,65	-80
NOTE: 'New' refers to the test procedure and requirements as described in the present document.				

Table 8 provides sensitivity values for LTE-V2X using Equation (5.3.1), see column "New sensitivity limit", given test-points outlined in example 2 and Table 4.

Table 8: Receiver sensitivity requirements following definitions from example 2 and Table 4

$\bar{R}_{eff\,Tx}$ range	I_MCS	Transport Block size (bits)	$\bar{R}_{eff\,Tx}$ (MBit/s)	'New' Sensitivity limit (dBm)
< 4,5 MBit/s	3	2 792	2,51	-87
	4	3 496	3,15	-86
	5	4 264	3,84	-85
	6	4 968	4,47	-84
NOTE: 'New' refers to the test procedure and requirements as described in the present document.				

6 Study on receiver selectivity requirements

6.1 Requirements as published in reference documents

6.1.1 Requirements in IEEE 802.11

IEEE Std 802.11-2016 [i.3] clause 17.3.10.3 defines the Adjacent Channel Rejection (ACR) and the Alternate Adjacent Channel Rejection (WACR) requirements based on signal's strength 3 dB above the modulation and coding scheme dependent minimum sensitivity (see clause 5.1.1 for details), 10 % PER and packets of 1000 bytes. ACR and AACR are defined as difference in power between the signal in the channel of interest and the signal in the interferer channel, which is also of type IEEE Std 802.11-2016. The minimum ACR and AACR requirements are defined for each modulation and coding scheme, for 5, 10 and 20 MHz channel bandwidth (for example 13 dB for ACR for QPSK ½ for 10 MHz channel) as per [i.3] Table 17-18.

IEEE Std 802.11-2016 [i.3] also defines optional enhanced ACR and AACR requirements, which are respectively 12 dB and 10 dB more stringent than the non-optional requirements as per [i.3] Table 17-19, as shown in Table 9.

Table 9: Limits for receiver adjacent channel rejection and alternate adjacent channel rejection as specified by IEEE 802.11-2016 [i.3] for 10 MHz channel

Modulation	Coding rate	Adjacent channel rejection (dB)	Alternate adjacent channel rejection (dB)	Enhanced adjacent channel rejection (dB)	Enhanced alternate adjacent channel rejection (dB)
BPSK	1/2	16	32	28	42
BPSK	3/4	15	31	27	41
QPSK	1/2	13	29	25	39
QPSK	3/4	11	27	23	37
16-QAM	1/2	8	24	20	34
16-QAM	3/4	4	20	16	30
64-QAM	2/3	0	16	12	26
64-QAM	3/4	-1	15	11	25

6.1.2 Requirements in ETSI EN 302 571 V2.1.1

The limits as defined in the published ETSI EN 302 571 [i.1], clause 4.2.7.2 are shown below in italic text:

"The receiver selectivity parameters under specified conditions shall be equal to or greater than the limits in Table 8".

Table 8: Limits for receiver adjacent channel rejection and alternate adjacent channel rejection

Modulation	*Coding rate*	*Adjacent channel rejection (dB)*	*Alternate adjacent channel rejection (dB)*
BPSK	*1/2*	*16*	*32*
BPSK	*3/4*	*15*	*31*
QPSK	*1/2*	*13*	*29*
QPSK	*3/4*	*11*	*27*
16-QAM	*1/2*	*8*	*24*
16-QAM	*3/4*	*4*	*20*
64-QAM	*2/3*	*0*	*16*
64-QAM	*3/4*	*-1*	*15*

NOTE: Limits only apply to the applicable modulations to the DUT.

The blocking level shall not be less than -30 dBm."

Observations:

- Requirements are expressed in form of Adjacent Channel Rejection (ACR) and Alternate Adjacent Channel Rejection (AACR).
- Requirements are expressed per ITS-G5 transmit rate (e.g. modulation coding scheme).
- Requirements are thus not expressed in a technology generic way, being only applicable to IEEE 802.11-2016 [i.3].
- The values specified for adjacent channel rejection and alternate adjacent channel rejection requirements are identical as the mandatory performance requirements indicated in table 17-18 of IEEE 802.11-2016 [i.3].
- Test procedure is identical to the one taught by IEEE 802.11-2016 [i.3] in clauses 17.3.10.3 and 17.3.10.4 (1 000 octets frame, etc.).
- The interfering signal is defined to also be a similar radio technology as the channel under test, meaning the interfering signal is also IEEE 802.11-2016 [i.3] OFDM PHY type of signal.

6.1.3 Requirements in 3GPP LTE Release-14

ETSI TS 136 101 [i.4] defines LTE Release14 User Equipment (UE) radio transmission and reception minimum performance requirements.

Clause 7.5.1G "Adjacent Channel Selectivity (ACS)" addresses Sidelink V2X direct communication (mode 4) selectivity requirements, as shown with the below italic text:

"The V2X UE shall fulfil the minimum requirement specified in Table 7.5.1G-1 for all values of an adjacent channel interferer up to -22 dBm. However it is not possible to directly measure the ACS, instead the lower and upper range of test parameters are chosen in Table 7.5.1G-2 and Table 7.5.1G-3 where the throughput shall be ≥ 95% of the maximum throughput of the reference measurement channels as specified in Annex A.8.2.

Table 7.5.1G-1: Adjacent channel selectivity for V2X

		Channel bandwidth					
Rx Parameter	Units	1.4 MHz	3 MHz	5 MHz	10 MHz	15 MHz	20 MHz
ACS	dB				33.0		27

"

Tables 7.5.1G-2 and 7.5.1G-3 are provided for reference in Annex A.

Clause 7.6.1.1G "In-band blocking" addresses Sidelink V2X direct communication (mode 4) in-band blocking requirements, as shown with the below italic text:

"The V2X UE throughput shall be ≥ 95% of the maximum throughput of the reference measurement channels as specified in Annex A.8.2 with parameters defined in Table 7.6.1.1G-1 and Table 7.6.1.1G-2.

Table 7.6.1.1G-1: In band blocking parameters

Rx parameter	Units	Channel bandwidth					
		1.4 MHz	3 MHz	5 MHz	10 MHz	15 MHz	20 MHz
Power in Transmission Bandwidth Configuration	dBm	$P_{REFSENS\_V2X}$ + channel bandwidth specific value below					
					6		9
$BW_{Interferer}$	MHz				10		10
$F_{Ioffset, case 1}$	M Hz				15+0.0025		15+0.005
$F_{Ioffset, case 2}$	MHz				25+0.0075		25+0.0025
NOTE 1: The interferer is QPSK modulated PUSCH containing data and reference symbols. Normal cyclic prefix is used. The data content shall be uncorrelated to the wanted signal and modulated according to clause 5 of TS36.211							

Table 7.6.1.1G-2: In-band blocking

E-UTRA V2X band	Parameter	Unit	Case 1	Case 2
	$P_{Interferer}$	dBm	-44	-44
	$F_{Interferer}$ (offset)	MHz	=-BW/2 - $F_{Ioffset,case 1}$ & =+BW/2 + $F_{Ioffset,case 1}$	≤-BW/2 - $F_{Ioffset,case 2}$ & ≥+BW/2 + $F_{Ioffset,case 2}$
47	$F_{Interferer}$	MHz	(NOTE 2)	F_{DL_low} -30 to F_{DL_high} + 30
NOTE 1: For certain bands, the unwanted modulated interfering signal may not fall inside the UE receive band, but within the first 15 MHz below or above the UE receive band NOTE 2: For each carrier frequency the requirement is valid for two frequencies: a. the carrier frequency -BW/2 - FIoffset, case 1 and b. the carrier frequency +BW/2 + FIoffset, case 1 NOTE 3: FInterferer range values for unwanted modulated interfering signal are interferer center frequencies				

"

The 'Case 1' entry with $F_{Ioffset, case 1}$ = ±(15 + BW/2) = ±20 MHz corresponds the frequency channels configuration of alternate adjacent channel tests defined in IEEE 802.11-2016 [i.3].

Observations:

- Requirements are expressed in form of adjacent channel selectivity (ACS).
- There is only one requirement per channel bandwidth, for a configuration (A.8.2) that is QPSK with coding rate of approximately 1/3.

6.1.4 Requirements in IEEE 802.11bd

The ACR & AACR selectivity requirements defined in IEEE 802.11bd (still under development) will most likely be identical to the ones from IEEE 802.11-2016 [i.3] for the MCS that overlap between IEEE 802.11p and IEEE 802.11bd.

6.1.5 Requirements in 3GPP 5G NR V2X

ETSI TS 138 101-1 [i.10] defines NR V2X User Equipment (UE) radio transmission and reception minimum performance requirements. Clause 7.5E defines adjacent selectivity requirements for V2X, as shown with the below italic table. Band n47 indicates the 5,9 GHz ITS band.

"Table 7.5E.1-1: Adjacent channel selectivity for NR V2X

RX parameter	Units	Channel bandwidth			
		10 MHz	20 MHz	30 MHz	40 MHz
ACS	dB	33.0	27.0	25.5	24.0

"

The Sidelink TX configuration for reference sensitivity tests is described in the below italic table.

"Table 7.5E.1-2: Test parameters for Adjacent channel selectivity for V2X, Case 1

RX parameter	Units	Channel bandwidth			
		10 MHz	20 MHz	30 MHz	40 MHz
Power in transmission bandwidth configuration	dBm	PREFSENS_V2X + 14 dB			
$P_{interferer}$	dBm	PREFSENS_V2X + 45.5 dB	PREFSENS_V2X + 39.5 dB	PREFSENS_V2X + 38.0 dB	PREFSENS_V2X + 36.5 dB
$BW_{interferer}$	MHz	10	10	10	10
$F_{interferer}$ (offset)	MHz	10 / -10	15 / -15	20 / -20	25 / -25
NOTE 1: The interferer is QPSK modulated PUSCH containing data and reference symbols. Normal cyclic prefix is used. NOTE 2: The absolute value of the interferer offset Finterferer (offset) shall be further adjusted to $(\lceil \lvert F_{interferer} \rvert / SCS \rceil + 0{,}5) SCS$ MHz with SCS the sub-carrier spacing of the wanted signal in MHz. The interferer is an NR signal with 15 kHz SCS.					

Table 7.5E.1-3: Test parameters for Adjacent channel selectivity for V2X, Case 2

RX parameter	Units	Channel bandwidth			
		10 MHz	20 MHz	30 MHz	40 MHz
Power in transmission bandwidth configuration	dBm	-56.5	-50.5	-49.0	-47.5
$P_{interferer}$	dBm	-25			
$BW_{interferer}$	MHz	10	10	10	10
$F_{interferer}$ (offset)	MHz	10 / -10	15 / -15	20 / -20	25 / -25
NOTE 1: The interferer is QPSK modulated PUSCH containing data and reference symbols. Normal cyclic prefix is used. NOTE 2: The absolute value of the interferer offset $F_{interferer}$ (offset) shall be further adjusted to $(\lceil \lvert F_{\text{interferer}} \rvert / SCS \rceil + 0{,}5) SCS$ MHz with SCS the sub-carrier spacing of the wanted signal in MHz. The interferer is an NR signal with 15 kHz SCS.					

"

Clause 7.6E-2 defines in-band blocking requirements for V2X, as shown with the below italic text. Band n47 indicates the 5,9 GHz ITS band.

"Table 7.6E.2.1-1: In-band blocking parameters for NR V2X

RX parameter	Units	Channel bandwidth			
		10 MHz	20 MHz	30 MHz	40 MHz
Power in transmission bandwidth configuration	dBm	$P_{REFSENS\_V2X}$ + channel bandwidth specific value below			
	dB	6	9	11	12
$BW_{interferer}$	MHz	10			
$F_{Ioffset, case 1}$	MHz	15			
$F_{Ioffset, case 2}$	MHz	25			
NOTE 1: The interferer is QPSK modulated PUSCH containing data and reference symbols. Normal cyclic prefix is used.					

"

The Sidelink TX configuration for reference sensitivity tests is described in the below italic text.

"Table 7.6E.2.1-2: In-band blocking for NR V2X

NR band	*Parameter*	*Unit*	*Case 1*	*Case 2*
n38, n47	$P_{interferer}$	*dBm*	*-44*	*-44*
	$F_{interferer}$ *(offset)*	*MHz*	*-BW/2 -* $F_{Ioffset, case 1}$ *and* *BW/2 + FIoffset, case 1*	*≤ -BW/2 -* $F_{Ioffset, case 2}$ *and* *≥ BW/2 + FIoffset, case 2*
	$F_{interferer}$	*MHz*	*NOTE 2*	F_{DL_low} *- 30* *to* F_{DL_high} *+ 30*
NOTE 1: For certain bands, the unwanted modulated interfering signal may not fall inside the UE receive band, but within the first 15 MHz below or above the UE receive band. *NOTE 2: For each carrier frequency the requirement is valid for two frequencies:* *a. the carrier frequency -BW/2 -* $F_{Ioffset, case 1}$ *and* *b. the carrier frequency +BW/2 + FIoffset, case 1* *NOTE 3: FInterferer range values for unwanted modulated interfering signal are interferer center frequencies* *NOTE 4: The absolute value of the interferer offset* $F_{interferer}$ *(offset) shall be further adjusted to* $\left(\left\lceil \left\|F_{\text{interferer}}\right\| / SCS \right\rceil + 0.5\right) SCS$ *MHz with SCS the sub-carrier spacing of the wanted signal in MHz. The interferer is an NR signal with 15 kHz SCS.*				

"

The entry 'Case 1' with $F_{Ioffset, case 1} = \pm (15 + BW/2) = \pm 20$ MHz corresponds the frequency channels configuration of alternate adjacent channel tests defined in IEEE 802.11-2016 [i.3].

Observations:

- The ACR requirements values defined in 5G NR V2X are similar from the ones defined in LTE-V2X.

Table 10: Comparison of LTE-V2X and 5G NR V2X receiver ACR requirements for 10 MHz channel

Standard	**Minimum ACR for 10 MHz channel spacing (dBm)**
LTE-V2X	33
5G NR V2X	33

- The interfering signal is defined as PUSCH (uplink, not sidelink) with QPSK signal.
- The AACR parameters (thus requirements) values defined in 5G NR V2X are similar from the ones defined in LTE-V2X.

Table 11: Comparison of LTE-V2X and 5G NR V2X receiver AACR parameters for 10 MHz channel

Standard	**AACR: $P_{Interferer}$**
LTE-V2X	-44
5G NR V2X	-44

6.2 Comparison of ITS-G5 and LTE-V2X selectivity values

This clause provides a comparison of the selectivity requirements based on the results obtained from clause B.5. The following Figure 6 and Figure 7 provide a comparison of the ITS-G5 and LTE-V2X ACR and AACR requirements, respectively.

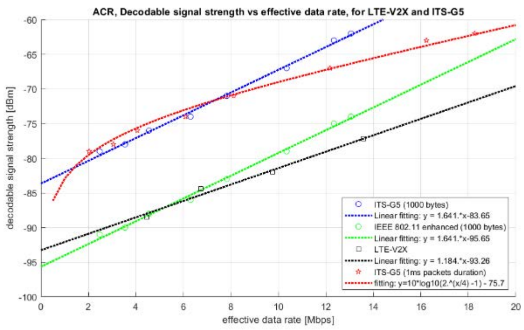

Figure 6: Comparison of ITS-G5 and LTE-V2X decodable signal strengths for ACR tests

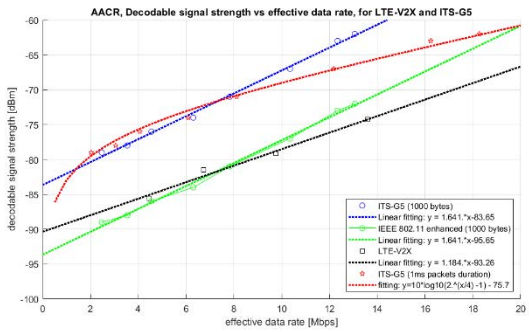

Figure 7: Comparison of ITS-G5 and LTE-V2X decodable signal strengths for AACR tests

It can be remarked that the first three series of Figure 6 and Figure 7 have the shape of a straight line (thus linear fitting is reasonable). Furthermore, the 'ITS-G5 enhanced' series are well aligned with the LTE-V2X series. The margins between the ITS-G5 and the ITS-G5 enhanced for ACR and AACR are the 12 and 10 dB differences that can be observed in clause 6.1.1.

Also, when plotting the ITS-G5 ACR values entries against the effective throughput using 1 ms packet (red pentagon stars), a change in shape is observed and a different fitting in the form of $y = 10\log_{10}\left(2^{\frac{\bar{R}_{\text{eff Tx}}}{4}\frac{1}{[MBit/s]}} - 1\right) - 75{,}7\ dB$ is tested with a good match.

Thus, generic selectivity limit functions could be derived and used to define the ACR and AACR limits requirements in a generic way, in order to be applicable to any technology, and depending only on the effective data rate.

6.3 Recommendations for receiver ACR and AACR selectivity tests

6.3.1 Test method

The ACR and AACR tests are measured by setting the desired signal's strength 6 dB above the effective data-rate-dependent sensitivity limit specified in clause 5.3 and raising the power of the interfering CW signal until 10 % PER is caused. The difference in power between the signals in the interfering channel and the desired channel is the corresponding ACR or AACR. The test procedure for each data-rate test point is further detailed in clause I.3.

For consistency in the sensitivity and selectivity test procedure definitions, it is proposed that the approach taken for ACR and AACR selectivity tests is aligned with the approach taken for sensitivity tests defined in clause 5.3. In particular, it is proposed that the term effective data rate $\bar{R}_{eff\,Tx}$ is used in a generic way to define the effective throughput, applicable to ITS-G5, LTE-V2X and future protocols regardless of their packet structure and packet sizes used for testing. The term effective data rate $\bar{R}_{eff\,Tx}$ is defined by Equation (5.2.1), which can be translated to Equation (5.2.2) for LTE-V2X. Also, it is proposed that technologies that can adjust packet duration set it to be as close as possible to 1 ms, and technologies that have fixed packet size use multiple subframes to get to as close as possible to 1 ms, including management overhead as defined for example in clause F.4.3.2.

6.3.2 ACR selectivity requirements

It is proposed that the below Equation (6.3.3) is used for defining the ACR selectivity requirements. It is based on the equation (B.5.9) defining ACR test as $P_{interf} = P_{sensitive} + 6 + ACR\ (dBm)$, leading to:

$$ACR = P_{interf} - P_{sensitive} - 6 \quad (6.3.1)$$

P_{interf} is replaced by -63 dBm and $P_{sensitive}$ by Equation (5.2.3). An offset of 3 dB is added to make the requirement more stringent and reflect a reduction in the implementation margin from 12 to 9 dB. Finally, a rounding operation is used to ensure integer values only (the rounding is realized adding +1/2 and using the flooring operator '⌊ ⌋'), the ACR_{req} can be derived as:

$$ACR_{req} = \left\lfloor -63\ dBm - \left(10\log_{10}\left(2^{\frac{\bar{R}_{\text{eff Tx}}}{4}\frac{1}{[MBit/s]}} - 1\right) - 81{,}3\ dB - 3\ dB\right) - 6\ dB + \frac{1}{2}\right\rfloor \quad (6.3.2)$$

Which can be further processed as:

$$ACR_{req} = \left\lfloor -10\log_{10}\left(2^{\frac{\bar{R}_{\text{eff Tx}}}{4}\frac{1}{[MBit/s]}} - 1\right) + 15{,}8\right\rfloor dB \quad (6.3.3)$$

It can be noticed that this theoretical formula Equation (6.3.3) is well aligned with the empirical formula (B.5.15).

6.3.3 AACR selectivity requirements

It is proposed that the below Equation (6.3.6) is used for defining the ACR selectivity requirements. It is based on the equation (B.5.25) defining AACR test as $P_{interf} = P_{sensitive} + 6 + AACR\ (dBm)$, leading to:

$$AACR = P_{interf} - P_{sensitive} - 6 \quad (6.3.4)$$

P_{interf} is replaced by -47 dBm and $P_{sensitive}$ by Equation (5.2.3). An offset of 2,5 dB is added to make the requirement more stringent and reflect a reduction in the implementation margin from 12 to 9 dB. Finally, a rounding operation is used to ensure integer values only (the rounding is realized adding +1/2 and using the flooring operator '⌊ ⌋'), the $AACR_{req}$ can be derived as:

$$AACR_{req} = \left\lfloor -47\ dBm - \left(10\log_{10}\left(2^{\frac{\bar{R}_{\text{eff Tx}}}{4}\frac{1}{[MBit/s]}} - 1\right) - 81{,}3\ dB - 2{,}5\ dB\right) - 6\ dB + \frac{1}{2}\right\rfloor \quad (6.3.5)$$

$$AACR_{req} = \left\lfloor -10\log_{10}\left(2^{\frac{\bar{R}_{\text{eff Tx}}}{4}\frac{1}{[MBit/s]}} - 1\right) + 31{,}3\right\rfloor dB \quad (6.3.6)$$

It can be noticed that this theoretical formula Equation (6.3.6) is well aligned with the empirical formula (B.5.31).

6.3.4 Interference Signal for selectivity tests

Basis for the test method is originating from RLAN 2,4 GHz [i.13] receiver blocking tests (clause 4.3.1.12 and clause 5.4.11).

The interference signal used in the ACR and AACR selectivity tests is a CW signal with a 100 % duty cycle.

The CW interferer frequency f_1 is located in the interferer channel, at 1 MHz from the center of the interferer channel towards the channel under test. If this first test is not successful, a second test is carried out where the CW interferer frequency f_2 is located in the interferer channel, at 0,5 MHz from the center of the interferer channel, away from the channel under test, as illustrated in Figure 8.

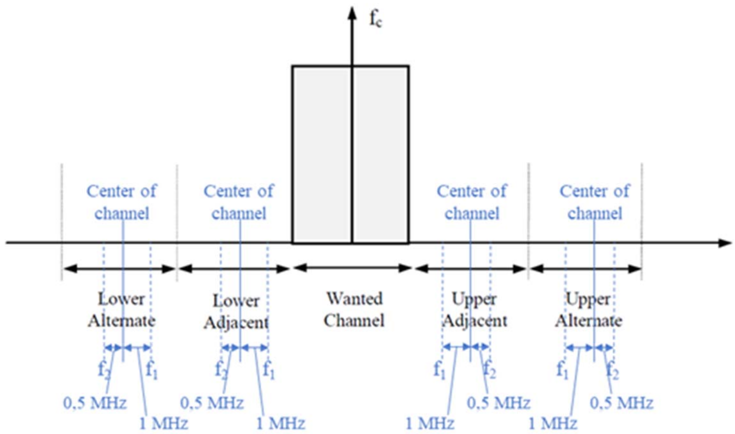

Figure 8: Adjacent and alternate channel CW interferer frequency definitions

6.3.5 Data-rate test-points

The proposed data-rate test-points are described in Table 12 and Table 13. The associated ACR and AACR selectivity limits are obtained from Equations (6.3.3) and (6.3.6) respectively. One way of testing is to test three test-points, as described in example 1 and in Table 12. Another way of testing is to have only one test-point, as described in example 2 and in Table 13.

EXAMPLE 1: Three test-points, as shown in Table 12 are defined as having an effective data rate R_{eff} < 3,5 MBit/s, 3,5 MBit/s to 4,5 MBit/s and > 4,5 MBit/s respectively. This option is aligned with the three test-points defined in example 1 for the sensitivity tests, where the selectivity limit functions which have the shape of a straight line after an initial bend at the lower rates (below 4,5 MBits/s). The three test-points aim at capturing a lower bound average effective data rate, a typical data-rate and an upper-bound data-rate (ideally the highest operational effective data rate of the DUT for test point).

Table 12: Proposal for testing selectivity with multiple data-rate test points

$\bar{R}_{eff\,Tx}$
< 3,5 MBit/s
3,5 MBit/s to 4,5 MBit/s
> 4,5 MBit/s

EXAMPLE 2: One test-point, as shown in Table 13 is defined as having an effective data rate R_{eff} < 4,5 MBit/s. This option promotes only one test-point as Doppler and fading effects, which are dominating at higher MCS values, are not considered in such a test setup.

Table 13: Proposal for testing selectivity with single data-rate test point

$\bar{R}_{eff\,Tx}$
< 4,5 MBit/s

6.4 Example derivation of data-rate test points

6.4.1 Derived data-rate test points and selectivity limits for ITS-G5

Table 14 provides ACR and AACR selectivity values for ITS-G5 using Equations (6.3.3) and (6.3.6), see column "New selectivity limit", given test-points outlined in example 1 and Table 12. Further, Table 12 tabulates all possible MCS for ITS-G5 together with the ACR and AACR selectivity values stemming from ETSI EN 302 571 [i.1] (column "Old sensitivity limits") defined for 1 000 bytes packets. It should be noted that for certain data-rate test points from Table 12, several MCS may be used. Packet duration is set to 1 ms, including management overhead as defined in clause F.4.3.2.

Table 14: Receiver selectivity requirements following definitions from example 1 and Table 12

$\bar{R}_{eff\,Tx}$ range	MCS	Nominal data rate (MBit/s)	Packet size (bytes)	$\bar{R}_{eff\,Tx}$ (MBit/s)	New ACR limit (dB)	New AACR limit (dB)	Old ACR limit (dB)	Old AACR limit (dB)
< 3,5 MBit/s	MCS 0 (BPSK ½)	3,0	279	2,0	19	35	16	32
	MCS 1 (BPSK ¾)	4,5	420	3,0	17	32	15	31
3,5 MBit/s to 4,5 MBit/s	MCS 2 (QPSK ½)	6,0	561	4,1	15	31	13	29
> 4,5 MBit/s	MCS 3 (QPSK ¾)	9,0	843	6,1	13	28	11	27
	MCS 4 (16-QAM ½)	12,0	1 125	8,1	10	26	8	24
	MCS 5 (16-QAM ¾)	18	1 689	12,2	7	22	4	20
	MCS 6 (64-QAM 2/3)	24	2 253	16,3	3	19	0	16
	MCS 7 (64-QAM ¾)	27	2 535	18,3	2	17	-1	15
NOTE: "New ACR limits" and "New AACR limits" refer to the test procedure and requirements as described in the present document. "Old ACR limits" and "Old AACR limits" refer to the test procedure and requirements described in ETSI EN 302 571 [i.1], which defines 1 000 bytes packets and is thus only related to the MCS column of this table. Such columns are provided only for information and cannot be compared directly to the "New ACR limits" and "New AACR limits" values.								

Table 15 provides ACR and AACR selectivity values for ITS-G5 using Equations (6.3.3) and (6.3.6), see column "New selectivity limit", given test-points outlined in example 2 and Table 13.

Table 15: Receiver selectivity requirements following definitions from example 2 and Table 13

$\bar{R}_{eff\,Tx}$ range	MCS	Nominal data rate (MBit/s)	Packet size (bytes)	$\bar{R}_{eff\,Tx}$ (MBit/s)	New ACR limit (dB)	New AACR limit (dB)	Old ACR limit (dB)	Old AACR limit (dB)
< 4,5 MBit/s	MCS 0 (BPSK ½)	3,0	279	2,0	19	35	16	32
	MCS 1 (BPSK ¾)	4,5	420	3,0	17	32	15	31
	MCS 2 (QPSK ½)	6,0	561	4,1	15	31	13	29
NOTE: "New ACR limits" and "New AACR limits" refer to the test procedure and requirements as described in the present document. "Old ACR limits" and "Old AACR limits" refer to the test procedure and requirements described in ETSI EN 302 571 [i.1], which defines 1 000 bytes packets, and is thus only related to the MCS column of this table. Such columns are provided only for information and cannot be compared directly to the "New ACR limits" and "New AACR limits" values.								

6.4.2 Comparison between the "old" and "new" selectivity limits for ITS-G5

As highlighted in the NOTE entries of Table 14 and Table 15, the "New ACR limit" and "New AACR limit" requirements are derived from Equations (6.3.3) and (6.3.6), assuming 1 ms packet duration, while the "Old ACR limit" and "Old AACR limits" originate from ETSI EN 302 571 [i.1] defined for 1 000 bytes packets.

Figure 9 provides a comparison of the "old" and "new" ACR selectivity limits for ITS-G5.

The blue triangle-shape markers depict the "Old ACR limits" from ETSI EN 302 571 [i.1] defined for 1 000 bytes packets. The blue dotted line is a linear fitting of the blue triangle-shape markers. The green line depicts the "New ACR limit" requirements derived using Equation (6.3.3) assuming 1 ms packet duration. It can be remarked that this curve has a staircase shape due to the rounding operation (realized with +1/2 & usage of the floor operator) in Equation (6.3.3). The black circles markers show application of the Equation (6.3.3) for ITS-G5 MCS (not all such entries needed to be tested, according to example 1 and Table 12 or according to example 2 and Table 13).

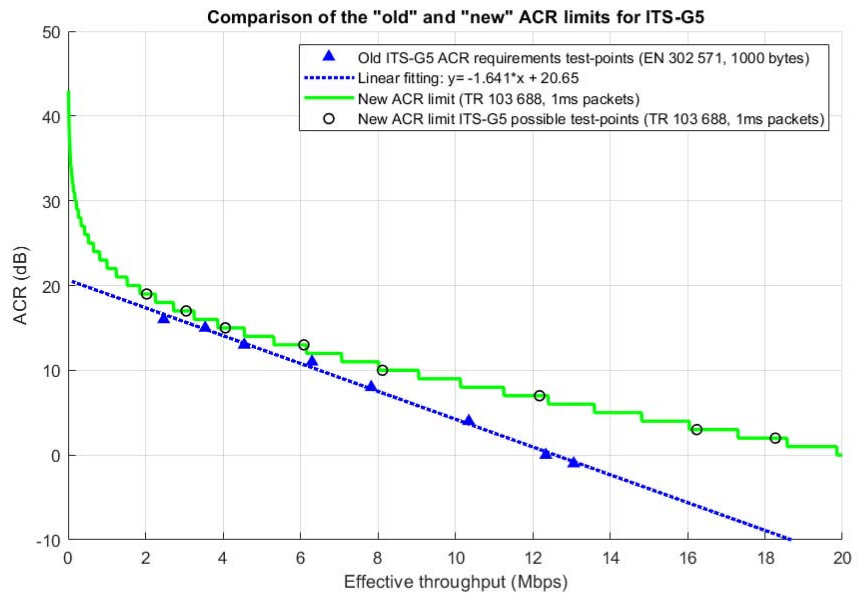

Figure 9: Comparison of the "old" and "new" ACR limits for ITS-G5

Figure 10 provides a comparison of the "old" and "new" AACR selectivity limits for ITS-G5.

The blue triangle-shape markers depict the "Old ACR limits" from ETSI EN 302 571 [i.1] defined for 1 000 bytes packets. The blue dotted line is a linear fitting of the blue triangle-shape markers. The green line depicts the "New AACR limit" requirements derived using Equation (6.3.6) assuming 1 ms packet duration. It can be remarked that this curve has a staircase shape due to the rounding operation (realized with +1/2 and usage of the floor operator) in Equation (6.3.6). The black circles markers show application of the Equation (6.3.6) for ITS-G5 MCS (not all such entries needed to be tested, according to example 1 and Table 12 or according to example 2 and Table 13).

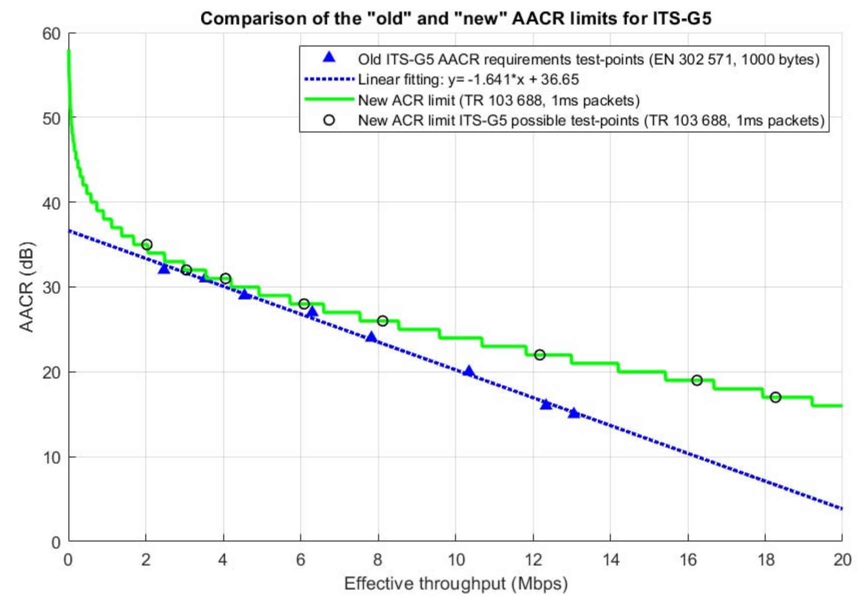

Figure 10: Comparison of the "old" and "new" AACR limits for ITS-G5

6.4.3 Derived data-rate test points and selectivity limits for LTE-V2X

Table 16 provides ACR and AACR selectivity values for LTE-V2X using Equations (6.3.3) and (6.3.6), see column "New sensitivity limit", given test-points outlined in example 1 and Table 12. It should be noted that for certain data-rate test points, several modulation and coding schemes may be used. It is assumed that LTE packet occupies all subchannels, and that the MCS range 0-11 is available.

Table 16: Receiver selectivity requirements following definitions from example 1 and Table 12

$\bar{R}_{eff\,Tx}$ range	I_MCS	Transport Block size (bits)	$\bar{R}_{eff\,Tx}$ (MBit/s)	New ACR limit (dB)	New AACR limit (dB)
< 3,5 MBit/s	3	2 792	2,51	18	33
	4	3 496	3,15	17	32
3,5 MBit/s to 4,5 MBit/s	5	4 264	3,84	16	31
	6	4 968	4,47	15	30
> 4,5 MBit/s	7	5 992	5,39	13	29
	8	6 712	6,04	13	28
	9	7 480	6,73	12	27
	10	8 504	7,65	11	26
	11	8 504	7,65	11	26
NOTE: "New ACR limits" and "New AACR limits" refer to the test procedure and requirements as described in the present document.					

Table 17 provides ACR and AACR selectivity values for LTE-V2X using Equations (6.3.3) and (6.3.6), see column "New sensitivity limit", given test-points outlined in example 2 and Table 13.

Table 17: Receiver selectivity requirements following definitions from example 2 and Table 13

$\bar{R}_{eff\,Tx}$ range	I_MCS	Transport Block size (bits)	$\bar{R}_{eff\,Tx}$ (MBit/s)	New ACR limit (dB)	New AACR limit (dB)
< 4,5 MBit/s	3	2 792	2,51	18	33
	4	3 496	3,15	17	32
	5	4 264	3,84	16	31
	6	4 968	4,47	15	30
NOTE: "New ACR limits" and "New AACR limits" refer to the test procedure and requirements as described in the present document.					

7 Conclusions

The present document studies the requirements on the receiver sensitivity, adjacent channel rejection and the alternate adjacent channel rejection.

The sensitivity and selectivity requirements as expressed in various standards and technical specifications are reviewed, including ITS-G5 as defined in ETSI EN 302 571 [i.1], IEEE 802.11-2016 [i.3], IEEE 802.11bd (still under development), 3GPP LTE-V2X release 14 [i.4] and 3GPP NR V2X [i.10].

All these requirements are post-processed to allow for a comparison, as a direct comparison is not possible due to differences in their respective test procedures and waveforms. From these comparisons, it is concluded that ITS-G5 and LTE-V2X requirements are in fact well aligned, and that newer technologies 5G NR V2X and IEEE 802.11bd are also very close from a receiver requirements perspective.

It is demonstrated that it is possible to derive receiver requirements formulas by means of mathematical computations, both for the sensitivity as well as for the ACR and AACR selectivity tests. It is also shown that it is possible to slightly tighten such receiver requirements (compared to ETSI EN 302 571 [i.1]) both for sensitivity and selectivity requirements.

Since the proposed sensitivity and selectivity requirements formulas are solely based on the effective data rate, it is concluded that it is technically possible to define such receiver requirements and associated tests for demonstrating compliance in a technology neutral manner, both for the sensitivity as well as for the ACR and AACR selectivity tests.

Thus, a major outcome of the present document are the Equations (5.3.1), (6.3.3) and (6.3.6) defining the receiver sensitivity, ACR and AACR selectivity requirements, respectively.

Two example options are provided regarding the definition of the data rate test points: example 1 proposes three test-points (< 3,5 MBit/s, 3,5 MBit/s to 4,5 MBit/s and > 4,5 MBit/s), while example 2 proposes one test-point.

Annex A: 3GPP adjacent selectivity tests tables (ETSI TS 136 101)

The below italic tables are extracted from ETSI TS 136 101 [i.4], clause 7.3G.

"Table 7.5.1G-2: Test parameters for Adjacent channel selectivity for V2X, Case 1

Rx Parameter	*Units*	*Channel bandwidth*					
		1.4 MHz	*3 MHz*	*5 MHz*	*10 MHz*	*15 MHz*	*20 MHz*
Power in Transmission Bandwidth Configuration	*dBm*	*PREFSENS_V2X + 14 dB*					
$P_{Interferer}$	*dBm*				$P_{REFSENS\_V2X}$ +45.5dB		$P_{REFSENS\_V2X}$ +39.5dB
$BW_{Interferer}$	*MHz*				*10*		*10*
$F_{Interferer}$ *(offset)*	*MHz*				*10+0.0125 / -10-0.0125*		*15+0.0075 / -15-0.0075*
NOTE 1: The interferer is QPSK modulated PUSCH containing data and reference symbols. Normal cyclic prefix is used. The data content shall be uncorrelated to the wanted signal and modulated according to clause 5 of TS36.211.							

Table 7.5.1G-3: Test parameters for Adjacent channel selectivity for V2X, Case 2

Rx Parameter	*Units*	*Channel bandwidth*					
		1.4 MHz	*3 MHz*	*5 MHz*	*10 MHz*	*15 MHz*	*20 MHz*
Power in Transmission Bandwidth Configuration	*dBm*				*-53.5*		*-47.5*
$P_{Interferer}$	*dBm*	*-22*					
$BW_{Interferer}$	*MHz*				*10*		*10*
$F_{Interferer}$ *(offset)*	*MHz*				*10+0.0125 / -10-0.0125*		*15+0.0075 / -15-0.0075*
NOTE 1: The interferer is QPSK modulated PUSCH containing data and reference symbols. Normal cyclic prefix is used. The data content shall be uncorrelated to the wanted signal and modulated according to clause 5 of TS 36.211.							

"

Annex B: Relationship between ACS and ACR

B.1 Introduction

3GPP LTE-V2X [i.4] and IEEE 802.11-2016 [i.3] use two different measures for the receiver's ability to receive a wanted signal at its assigned channel frequency in the presence of an adjacent channel interfering signal at a given offset from the centre frequency of the assigned channel, without the interfering signal causing a degradation of the receiver performance beyond a specific limit. 3GPP LTE-V2X [i.4] defines Adjacent Channel Selectivity (ACS), while IEEE 802.11-2016 [i.3] defines Adjacent Channel Ratio (ACR).

B.2 ACS in LTE-V2X Release 14

For LTE-V2X, ETSI TS 136 101 [i.4] Table 7.5.1G-3 is used to test ACS with a large (in terms of power) adjacent interferer.

In ETSI TS 136 101 [i.4], tables 7.5.1G-1 and 7.5.1G-2 are used for testing ACS with a small (in terms of power) adjacent interferer and investigate the 10 MHz case. For this case, using the reference sensitivity power $P_{REFSENS\_V2X}$, in-band power and the interferer power are given by:

$$P_{inband} = P_{REFSENS\_V2X} + 14\ dB \qquad (B.2.1)$$

and

$$P_{interferer} = P_{REFSENS\_V2X} + 45{,}5\ dB \qquad (B.2.2)$$

respectively.

Therefore, the value of ACS can be interpreted as the minimum wanted interferer reduction P_{i_wanted} for a given interferer power $P_{interferer}$:

$$ACS = P_{interferer} - P_{i\_wanted} \qquad (B.2.3)$$

Figure B.1 gives an overview of the relationship between different variables.

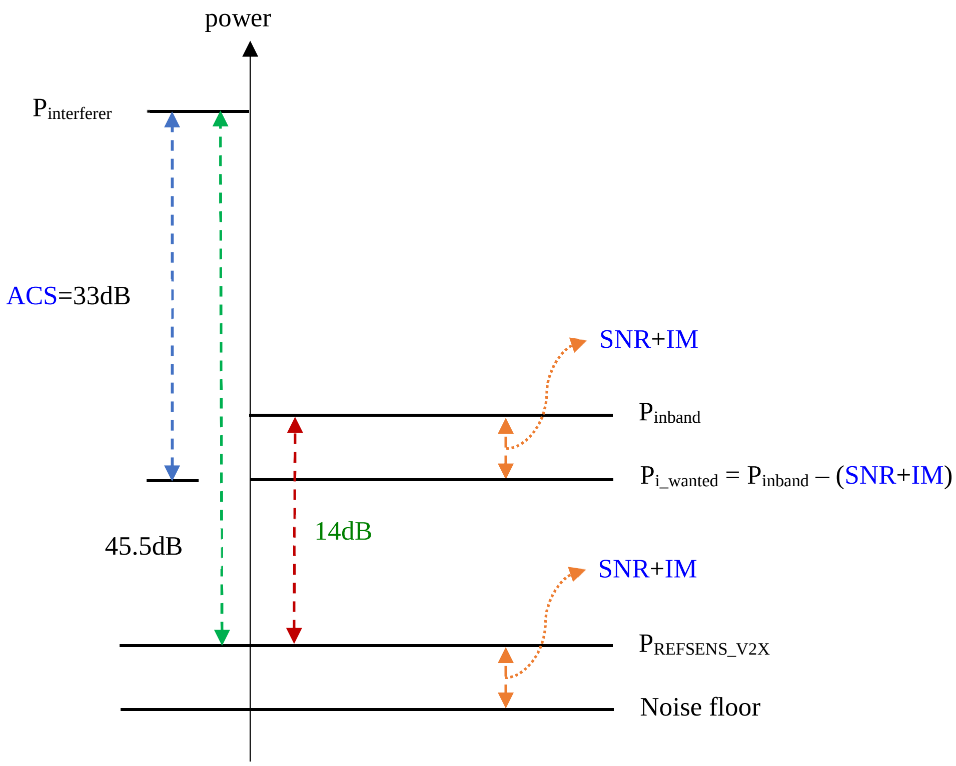

Figure B.1: Visualization of relationship between different variables for LTE-V2X

It can be observed from Figure B.1 that the ACS can be expressed as a function of the in-band power, the signal-to-noise ratio (SNR) required for the reception within the specific limit, and the implementation margin (IM) as:

$$\mathrm{ACS} = \mathrm{P}_{\mathrm{Interfer}} - (\mathrm{P}_{\mathrm{inband}} - \mathrm{SNR} - \mathrm{IM}) \quad (B.2.4)$$

With the definition of ACR, $\mathrm{ACR} = \mathrm{P}_{\mathrm{Interfer}} - \mathrm{P}_{\mathrm{inband}}$, the following relationship is obtained:

$$\mathrm{ACS} = \mathrm{ACR} + (\mathrm{SNR} + \mathrm{IM}) \quad (B.2.5)$$

This can be also written as:

$$\mathrm{ACS} = \mathrm{ACR} + \mathrm{P}_{\mathrm{REFSENS\_V2X}} - \mathrm{NoiseFloor} \quad (B.2.6)$$

Here, NoiseFloor denotes the thermal noise including the noise figure. To derive the 3GPP requirements a noise figure of 12 dB has been assumed.

B.3 ACR in IEEE 802.11

The text description of the test procedure in IEEE 802.11-2016 [i.3] can be translated into the following Figure B.2.

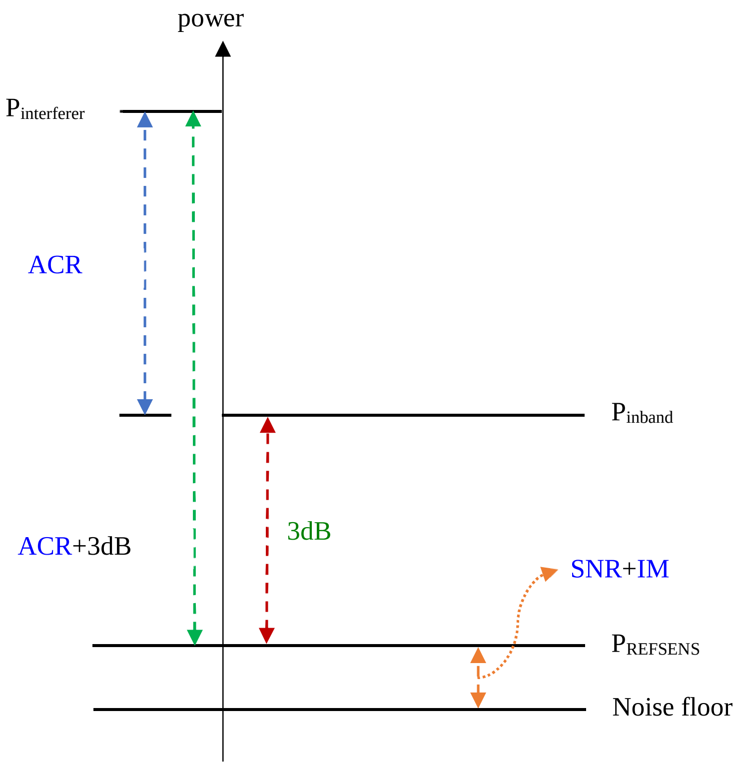

Figure B.2: Visualization of relationship between different variables for IEEE 802.11-2016 [i.3]

As can be observed from Figure B.2, the ACR can be expressed as a function of the reference sensitivity power $P_{REFSENS}$ as:

$$ACR = P_{interferer} - P_{inband} = P_{interferer} - P_{REFSENS} - 3\text{ dB} \quad (B.3.1)$$

Furthermore, the reference sensitivity power can be expressed as a function of the noise floor, the SNR and the Implementation Margin (IM):

$$P_{REFSENS} = NoiseFloor + SNR + IM \quad (B.3.2)$$

B.4 Relationship between ACR and ACS

To obtain the equivalent ACS value for IEEE 802.11 from the ACR value, the SNR and implementation margin can be considered as:

$$ACS = ACR + (SNR + IM) = ACR + P_{REFSENS} - NoiseFloor \quad (B.4.1)$$

Similarly, the equivalent ACR value for LTE-V2X can be computed as:

$$ACR = ACS - (SNR + IM) = ACS - P_{REFSENS_{V2X}} + NoiseFloor \quad (B.4.2)$$

From both equations, it can be observed that ACS and ACR are related via the required SNR (plus IM) for a reliable transmission or equivalently the reference sensitivity power.

However, the fundamental problem to directly compare the IEEE 802.11 ACR with the 3GPP LTE ACS is the reference sensitivity definition. The LTE-V2X release 14 specification [i.4] defines only one reference sensitivity value for QPSK modulation with a code rate close to 1/3. In contrast, IEEE 802.11-2016 [i.3] defines the reference sensitivity, also referred to as minimum sensitivity in Table 17-18, for all supported reference MCSs.

It is worth noting, that the ACS definition is not the same as ACR. The ACS value includes an Implementation Margin (IM) and the SNR required to decode the reference MCS.

Since this relationship depends on the reference sensitivity definition of each technology, i.e. the implementation margin and the SNR required to decode the reference MCS, it is not possible to directly compare both values.

It should also be noticed that IEEE 802.11-2016 [i.3] tests ACR with a PER ≤ 10 % (PRR ≥ 90 %) while 3GPP instruct a throughput ≥ 95 % of nominal throughput (PRR ≥ 95 %).

In order to be able to relate the two definitions, one would need a well-defined test scenario for sensitivity for a given modulation and coding scheme, with a given IM.

B.5 Comparison of LTE-V2X ACS/in-band blocking with ITS-G5 ACR/AACR requirements

B.5.1 3GPP channel selectivity test parameters

As outlined in clause B.2, Annex A, Table 7.5.1G-2 in ETSI TS 136 101 [i.4] defines the adjacent channel selectivity test parameters. Based on those parameters an equivalent Adjacent Channel Rejection (ACR) can be calculated as:

$$\mathrm{ACR} = \mathrm{P\_interferer} - \mathrm{P\_in\_Tx\_BW} = (\mathrm{PREFSENS} + 45{,}5\ \mathrm{dBm}) - (\mathrm{PREFSENS} + 14\ \mathrm{dBm}) = 31{,}5 \quad \text{(B.5.1)}$$

This ACR value is valid for an interferer power level of -44,9 dBm and a desired signal power level of -76,4 dBm, where the desired signal is modulated with QPSK and uses a code rate R = 1/3. The reference sensitivity level for LTE-V2X is $P_{REFSENS}$ = -90,4 dBm.

Similarly, Table 7.6.1.1G-1 and Table 7.6.1.1G-2 from ETSI TS 136 101 [i.4] define the in-band blocking requirements, cf. also clause 6.1.3. Based on the test requirements, an Alternate Adjacent Channel Rejection (AACR) value can be calculated as:

$$\mathrm{AACR} = \mathrm{P\_interferer} - \mathrm{P\_in\_Tx\_BW} = -44\ \mathrm{dBm} - (-90{,}4\ \mathrm{dBm} + 6\ \mathrm{dBm}) = 40{,}4 \quad \text{(B.5.2)}$$

This AACR value is valid for an interferer power level of -44,0 dBm and a desired signal power level of -84,4 dBm, where the desired signal is modulated with QPSK and uses a code rate R = 1/3.

A direct comparison of the ACR and AACR values defined for LTE-V2X and ITS-G5 is not possible since both depend on the choice of the modulation and coding scheme (MCS). This is also directly visible in clause 6.1.1, where the tables for ITS-G5 show ACR and AACR as a function of the MCS. For a fair comparison of the requirements, clause 5.3.2 in 3GPP TR 36.786 [i.6] proposes a method how to do this comparison for the LTE-V2X ACS requirement and the "normal" ITS-G5 ACR receiver requirement. In the following this method is adopted and used to compare the LTE-V2X ACS requirement with the ITS-G5 ACR requirement in ETSI EN 302 571 [i.1]. Furthermore, the LTE-V2X in-band blocking requirement is compared with the ITS-G5 AACR adopting the same method.

The method proposed in in 3GPP TR 36.786 [i.6] proposes to perform the comparison for four MCS points, QPSK and 16-QAM with rates 1/2 & 3/4. To obtain the SNR required by LTE-V2X in the measurement reference channel, which is used for ACS and in-band blocking tests, for a BLock Error Rate (BLER) of 10 % has been averaged from multi-company simulation results. The required SNR denoted as SNR_{V2V} in the following is summarized in Table B.1.

Table B.1: Required SNR for LTE-V2X to achieve 10 % BLER in the measurement reference channel depending on the MCS according to 3GPP TR 36.786 [i.6]

Modulation	Coding rate	SNR_{V2V} (dB)
QPSK	1/2	-1,2
QPSK	3/4	2,9
16-QAM	1/2	5,3
16-QAM	3/4	10,1

B.5.2 Comparison of ACS and ACR

The selectivity conformance test is described in clause 5.3.7 of ETSI EN 302 571 [i.1]. The wanted signal is set at 3 dB above the sensitivity level and the interference signal is set at ACR dBc above the wanted signal, i.e.:

$$P_{signal} = P_{sensitive} + 3 \quad \text{(B.5.3)}$$

$$P_{interf} = P_{sensitive} + 3 + ACR \text{ (dBm)} \quad \text{(B.5.4)}$$

Taking $P_{sensitive}$ values for each MCS as defined by the required sensitivity in ETSI EN 302 571 [i.1], all the corresponding values can be computed and gathered in Table B.2.

Table B.2: ACR requirements from ETSI EN 302 571 [i.1] and interferer power level

Modulation	Coding rate	Required sensitivity (dBm)	ACR (dB)	P_{interf} (dBm) Equation (B.5.4)
BPSK	1/2	-85	16	-66
BPSK	3/4	-84	15	-66
QPSK	1/2	-82	13	-66
QPSK	3/4	-80	11	-66
16-QAM	1/2	-77	8	-66
16-QAM	3/4	-73	4	-66
64-QAM	2/3	-69	0	-66
64-QAM	3/4	-68	-1	-66

The ACR requirement for LTE-V2X, as derived above, is investigated at an interferer power level of -44,9 dBm and a desired signal power level of -76,4 dBm. In contrast for ITS-G5 with QPSK and rate 1/2 the interferer power level is -66 dBm and the desired signal power level is -82 dBm when setting the wanted signal is set at 3 dB above the sensitivity level.

Therefore, the conformance tests defined for both technologies operate at different power levels relative to the noise floor. This is considered when comparing both requirements hereafter.

First, the remaining interferer power level after the ACS has been considered is computed as:

$$P_{interf,\ remained} = P_{interf} - ACS = -66 \text{ dBm} - 33 \text{ dB} = -99 \text{ dBm} \quad \text{(B.5.5)}$$

The total noise and interference power is hence:

$$P_{I+N} = 10 \text{ x } \log10(\ 10\text{^}(-9,9) + 10\text{^}(-9,1)) = -90,4 \text{ dBm} \quad \text{(B.5.6)}$$

where the noise floor of -91 dBm is coming from a thermal noise of -104 dBm and an assumed noise figure of 13 dB. The expected minimum decodable input signal level can be computed as:

$$P_{decode} = P_{I+N} + SNR_{V2V} + IM = -87,9 \text{ dBm} + SNR_{V2V} \quad \text{(B.5.7)}$$

with SNR_{V2V} according to Table B.1 and the Implementation Margin (IM) assumed during LTE-V2X specification is 2,5 dB.

Table B.3 summarizes the expected decode signal strength for different MCSs with the requirements given by the ITS-G5 decode signal strength. Here, it is observed that the delta between the 3GPP LTE-V2X ACS requirement and existing ACR requirements in ETSI EN 302 571 [i.1] varies depending on the selected MCS.

Table B.3: Expected LTE-V2X decode signal strength for adjacent channel interference with -66 dBm for different MCSs

Modulation	Coding rate	ITS-G5 decodable signal strength (dBm)	LTE-V2X Expected decodable signal strength (dBm)	Delta
BPSK	1/2	-82	Not supported	
BPSK	3/4	-81	Not supported	
QPSK	1/2	-79	-89,1	10,1
QPSK	3/4	-77	-85,0	8,0
16-QAM	1/2	-74	-82,6	8,6
16-QAM	3/4	-70	-77,8	7,8
64-QAM	2/3	-66	Not supported	
64-QAM	3/4	-65	Not supported	

If the wanted signal is set at 6 dB above the sensitivity level and the interference signal is set at ACR dBc above the wanted signal, the following is obtained:

$$P_{signal} = P_{sensitive} + 6 \qquad (B.5.8)$$

$$P_{interf} = P_{sensitive} + 6 + ACR \text{ (dBm)} \qquad (B.5.9)$$

Taking $P_{sensitive}$ values for each MCS as defined by the required sensitivity in ETSI EN 302 571 [i.1], all the corresponding values can be computed and gathered in Table B.4.

Table B.4: ACR requirements from ETSI EN 302 571 [i.1] and interferer power level, with signal of interest 6 dB above the sensitivity limit

Modulation	Coding rate	Required sensitivity (dBm)	ACR (dB)	P_{interf} (dBm) Equation (B.5.9)
BPSK	1/2	-85	16	-63
BPSK	3/4	-84	15	-63
QPSK	1/2	-82	13	-63
QPSK	3/4	-80	11	-63
16-QAM	1/2	-77	8	-63
16-QAM	3/4	-73	4	-63
64-QAM	2/3	-69	0	-63
64-QAM	3/4	-68	-1	-63

For ITS-G5 with QPSK and rate ½, the interferer power level is -63 dBm and the desired signal power level is -79 dBm when setting the wanted signal is set at 6 dB above the sensitivity level.

First, the remaining interferer power level after the ACS has been considered is computed as:

$$P_{interf,\ remained} = P_{interf} - ACS = -63 \text{ dBm} - 33 \text{ dB} = -96 \text{ dBm} \qquad (B.5.10)$$

The total noise and interference power is hence:

$$P_{I+N} = 10 \times \log10(\ 10\text{^}(-9{,}6) + 10\text{^}(-9{,}1)) = -89{,}8 \text{ dBm} \qquad (B.5.11)$$

where the noise floor of -91 dBm is coming from a thermal noise of -104 dBm and an assumed noise figure of 13 dB. The expected minimum decodable input signal level can be computed as:

$$P_{decode} = P_{I+N} + SNR_{V2V} + IM = -87{,}3 \text{ dBm} + SNR_{V2V} \qquad (B.5.12)$$

with SNR_{V2V} according to Table B.1 and the Implementation Margin (IM) assumed during LTE-V2X specification is 2,5 dB.

Table B.5 summarizes the expected decode signal strength for different MCSs with the requirements given by the ITS-G5 decode signal strength. Here, it is observed that the delta between the 3GPP LTE-V2X ACS requirement and existing ACR requirements in ETSI EN 302 571 [i.1] varies depending on the selected MCS.

Table B.5: Expected LTE-V2X decode signal strength for adjacent channel interference with -63 dBm for different MCSs

Modulation	Coding rate	ITS-G5 decodable signal strength (dBm)	LTE-V2X Expected decodable signal strength (dBm)	Delta
BPSK	1/2	-79	Not supported	
BPSK	3/4	-78	Not supported	
QPSK	1/2	-76	-88,5	12,5
QPSK	3/4	-74	-84,4	10,4
16-QAM	1/2	-71	-82,0	11,0
16-QAM	3/4	-67	-77,2	10,2
64-QAM	2/3	-63	Not supported	
64-QAM	3/4	-62	Not supported	

Table B.6 below provides ITS-G5 parameters for the MCS configurations of Table B.5. It assumes 1 000 bytes per packet. Packet duration includes management overhead as defined in clause F.4.3.2. Effective data rate assumes 10 % PER.

Table B.6: ITS-G5 receiver sensitivity requirements for 1 000 bytes packets

MCS	Nominal data rate (MBit/s)	Packet size (bytes)	Packet duration (ms)	$\bar{R}_{eff\,Tx}$ (MBit/s)
MCS 0 (BPSK ½)	3	1 000	2,9195	2,47
MCS 1 (BPSK ½)	4,5	1 000	2,0315	3,54
MCS 2 (QPSK ½)	6	1 000	1,5835	4,55
MCS 3 (QPSK ¾)	9	1 000	1,1435	6,3
MCS 4 (16-QAM ½)	12	1 000	0,9195	7,83
MCS 5 (16-QAM ¾)	18	1 000	0,6955	10,35
MCS 6 (64-QAM 2/3)	24	1 000	0,5835	12,34
MCS 7 (64-QAM ¾)	27	1 000	0,5515	13,06

The following Table B.7 provides LTE-V2X parameters that have been used in 3GPP TR 36.785 [i.12] to map QPSK ½, QPSK ¾, 16-QAM ½ and 16-QAM ¾ configurations. The effective data rate $\bar{R}_{eff\,Tx}$ is normalized over the whole set of RB for LTE-V2X and assumes 10 % PER.

Table B.7: LTE-V2X parameters for QPSK ½, QPSK ¾, 16-QAM ½ and 16-QAM ¾ configurations

Target modulation and coding scheme (to match ITS-G5 MCS)	RBs	TBS	I_MCS	Effective coding rate	$\bar{R}_{eff\,Tx}$ (MBit/s)
QPSK ½	48	4 968	6	0,48	4,47
QPSK ¾	48	7 480	9	0,72	6,73
16-QAM ½	36	8 248	13	0,53	9,77
16-QAM ¾	27	8 760	17	0,75	13,59

Using the definition of the ITS-G5 and LTE-V2X configurations from Table B.6 and Table B.7, the following Figure B.3 provides a comparison of ITS-G5 (blue circles) and LTE-V2X (black rectangles) decodable signal strengths for ACR tests from Table B.6 and Table B.7 respectively. For ITS-G5, the decodable signal strength originating from enhanced ACR requirements is also provided (green circles, 12 dB more stringent than the normal values for ACR). A linear fitting is performed for these three series, and is displayed in dotted lines of the corresponding color.

In addition, another series has been created by adapting the ITS-G5 values, by using the effective data rates based on 1 ms packets (from Table 5) shown with the red pentagons, with a curve fitting in the shape of $y = 10\log_{10}\left(2^{\frac{\bar{R}_{\text{eff Tx}}}{4}\frac{1}{[MBit/s]}} - 1\right) - X\,dB$, based on the sensitivity Equation (5.3.1). The best value of X is found to be 75,7, leading to the curve fitting formula (B.5.13):

$$y = 10\log_{10}\left(2^{\frac{\bar{R}_{\text{eff Tx}}}{4}\frac{1}{[MBit/s]}} - 1\right) - 75{,}7\,dB \qquad \text{(B.5.13)}$$

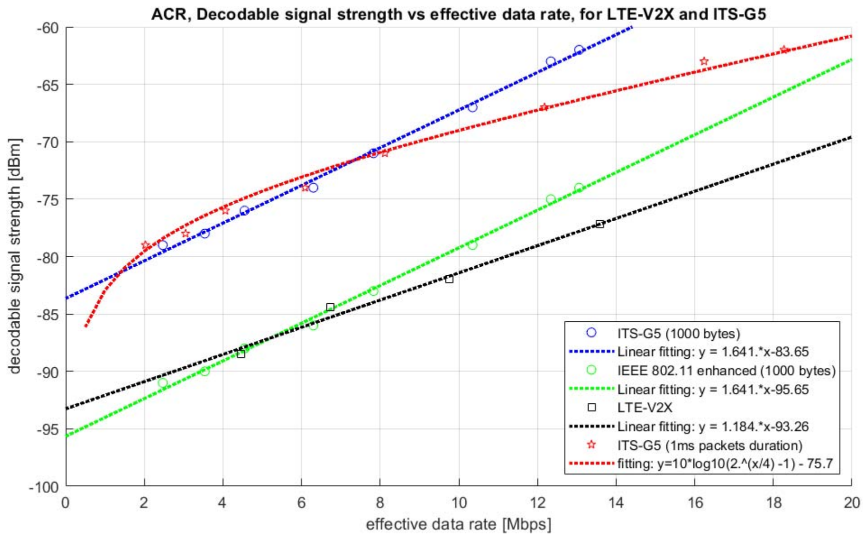

Figure B.3: Comparison of ITS-G5 and LTE-V2X decodable signal strengths for ACR tests, with signal of interest 6 dB above the sensitivity limit

It can be observed that:

- The first three series have the shape of a straight line (thus linear fitting is reasonable).
- The IEEE 802.11p enhanced and LTE-V2X values are fairly close.
- When plotting the ITS-G5 ACR values entries (y-axis) against the effective throughput using 1 ms packet (red pentagon stars), a change in shape is noticed, and the fitting $y = 10\log_{10}\left(2^{\frac{\bar{R}_{\text{eff Tx}}}{4}\frac{1}{[MBit/s]}} - 1\right) - 75{,}7\ dB$ is proposed.

From Equation (B.5.13), an 'empirical' ACR requirement formula can be derived as:

$$ACR_{req} = -(\text{fitting})dBm + P_{interf} + 3\ dB) \qquad \text{(B.5.14)}$$

Replacing (fitting) by formula (B.5.13), it can be derived that:

$$ACR_{req} = -\left(10\log_{10}\left(2^{\frac{\bar{R}_{\text{eff Tx}}}{4}\frac{1}{[MBit/s]}} - 1\right) - 75{,}7\ dB\right)dBm + P_{interf} + 3\ dB)$$

$$ACR_{req} = -\left(10\log_{10}\left(2^{\frac{\bar{R}_{\text{eff Tx}}}{4}\frac{1}{[MBit/s]}} - 1\right) - 75{,}7\ dB\right)dBm - 63\ \text{dBm} + 3\ dB)$$

Finally leading to a possible 'empirical' ACR requirement formula (B.5.15):

$$ACR_{req} = -10\log_{10}\left(2^{\frac{\bar{R}_{\text{eff Tx}}}{4}\frac{1}{[MBit/s]}} - 1\right) + 15{,}7\ dB \qquad \text{(B.5.15)}$$

B.5.3 Comparison of in-band blocking and AACR

To reuse the method proposed in in 3GPP TR 36.786 [i.6] to compare the in-band blocking with the AACR requirement an equivalent Alternate Adjacent Channel Selectivity (AACS) for the in-band blocking is computed. In the scope of 3GPP TR 36.786 [i.6] a comparison between the LTE-V2X in-band blocking requirement and the ITS-G5 AACS requirement has not been done.

The AACS is computed by using the identity from clause B.4:

$$\text{AACS} = \text{AACR} + \text{P}_{\text{REFSENS}_{\text{V2X}}} - \text{NoiseFloor} \qquad \text{(B.5.16)}$$

Replacing $\text{NoiseFloor} = \text{NoiseFigure} + \text{ThermalNoise}$ yields:

$$\text{AACS} = \text{AACR} + P_{\text{REFSENS}_{\text{V2X}}} - \text{NoiseFigure} - \text{ThermalNoise} \quad (B.5.17)$$

Using the LTE-V2X AACR value of 40,4 dB, the reference sensitivity value -90,4 dBm, a noise figure of 12 dB and the thermal noise for 10 MHz bandwidth, the alternate adjacent channel selectivity is obtained as:

$$\text{AACS} = 40{,}4\text{ dB} + (-90{,}4\text{ dBm}) - 12\text{ dB} - (-174\text{ dBm} + 10 \cdot \log_{10}(10 \cdot 10^6)) = 42{,}0\text{ dB} \quad (B.5.18)$$

This result means that the LTE-V2X in-band blocking requirement defines a 42 dB alternate adjacent channel selectivity which is 9 dB higher than the LTE-V2X ACS, which is 33 dB.

The selectivity conformance test is described in clause 5.3.7 of ETSI EN 302 571 [i.1]. The wanted signal is set at 3 dB above the sensitivity level and the interference signal is set at AACR dB above the wanted signal, i.e.:

$$P_{\text{signal}} = P_{\text{sensitive}} + 3 \quad (B.5.19)$$

$$P_{\text{interf}} = P_{\text{sensitive}} + 3 + \text{AACR (dBm)} \quad (B.5.20)$$

Taking $P_{\text{sensitive}}$ values for each MCS as defined by the required sensitivity in ETSI EN 302 571 [i.1], all the corresponding values can be computed and gathered in Table B.8.

Table B.8: AACR requirements from ETSI EN 302 571 [i.1] and interferer power level

Modulation	Coding rate	Required sensitivity (dBm)	AACR (dB)	P_{interf} (dBm) Equation (B.5.20)
BPSK	1/2	-85	32	-50
BPSK	3/4	-84	31	-50
QPSK	1/2	-82	29	-50
QPSK	3/4	-80	27	-50
16-QAM	1/2	-77	24	-50
16-QAM	3/4	-73	20	-50
64-QAM	2/3	-69	16	-50
64-QAM	3/4	-68	15	-50

The ACR requirement for LTE-V2X, as derived above, is investigated at an interferer power level of -44,0 dBm and a desired signal power level of -84,4 dBm. In contrast, for ITS-G5 with QPSK and rate 1/2 the interferer power level is -50 dBm and the desired signal power level is -82 dBm. Therefore, the conformance tests defined for both technologies operate at different power levels relative to the noise floor. The following equations elaborate on this matter for comparing both requirements.

First, the remaining interferer power level after the AACS has been considered is computed as:

$$P_{\text{interf, remained}} = P_{\text{interf}} - \text{AACS} = -50\text{ dBm} - 42\text{ dB} = -92\text{ dBm} \quad (B.5.21)$$

The total noise and interference power is hence:

$$P_{\text{I + N}} = 10 \text{ x } \log_{10}(10\text{^}(-9{,}2) + 10\text{^}(-9{,}1)) = -88{,}5\text{ dBm} \quad (B.5.22)$$

where the noise floor of -91 dBm is coming from a thermal noise of -104 dBm and an assumed noise figure of 13 dB. The expected minimum decodable input signal level can be computed as:

$$P_{\text{decode}} = P_{\text{I + N}} + \text{SNR}_{\text{V2V}} + \text{IM} = -86{,}0\text{ dBm} + \text{SNR}_{\text{V2V}} \quad (B.5.23)$$

with SNR_{V2V} according to Table B.1 and the Implementation Margin (IM) assumed during LTE-V2X specification is 2,5 dB.

Table B.9 summarizes the expected decode signal strength for different MCSs with the requirements given by the ITS-G5 decode signal strength. Here, it is observed that the delta between the 3GPP LTE-V2X in-band blocking requirement and existing AACR requirements in ETSI EN 302 571 [i.1] varies depending on the selected MCS.

Table B.9: Comparison of LTE-V2X and ITS-G5 signal strength needed to decode packets, for alternate adjacent channel interference with -50 dBm for different MCSs

Modulation	Coding rate	ITS-G5 decodable signal strength (dBm)	LTE-V2X Expected decodable signal strength (dBm)	Delta
BPSK	1/2	-82	Not supported	
BPSK	3/4	-81	Not supported	
QPSK	1/2	-79	-87,2	8,2
QPSK	3/4	-77	-83,1	6,1
16-QAM	1/2	-74	-80,7	6,7
16-QAM	3/4	-70	-75,9	5,9
64-QAM	2/3	-66	Not supported	
64-QAM	3/4	-65	Not supported	

If the wanted signal is set at 6 dB above the sensitivity level and the interference signal is set at ACR dBc above the wanted signal, the following is obtained:

$$P_{signal} = P_{sensitive} + 6 \quad \text{(B.5.24)}$$

$$P_{interf} = P_{sensitive} + 6 + AACR \text{ (dBm)}. \quad \text{(B.5.25)}$$

Taking $P_{sensitive}$ values for each MCS as defined by the required sensitivity in ETSI EN 302 571 [i.1], all the corresponding values can be computed and gathered in Table B.10.

Table B.10: AACR requirements from ETSI EN 302 571 [i.1] and interferer power level

Modulation	Coding rate	Required sensitivity (dBm)	AACR (dB)	P_{interf} (dBm) Equation (B.5.25)
BPSK	1/2	-85	32	-47
BPSK	3/4	-84	31	-47
QPSK	1/2	-82	29	-47
QPSK	3/4	-80	27	-47
16-QAM	1/2	-77	24	-47
16-QAM	3/4	-73	20	-47
64-QAM	2/3	-69	16	-47
64-QAM	3/4	-68	15	-47

The ACR requirement for LTE-V2X, as derived above, is investigated at an interferer power level of -44,0 dBm and a desired signal power level of -84,4 dBm. In contrast, for ITS-G5 with QPSK and rate 1/2 the interferer power level is -47 dBm and the desired signal power level is -79 dBm. Therefore, the conformance tests defined for both technologies operate at different power levels relative to the noise floor. The following equations elaborate on this matter for comparing both requirements.

First, the remaining interferer power level after the AACS has been considered is computed as:

$$P_{interf,\ remained} = P_{interf} - AACS = -47 \text{ dBm} - 42 \text{ dB} = -89 \text{ dBm} \quad \text{(B.5.26)}$$

The total noise and interference power is hence:

$$P_{I+N} = 10 \times \log_{10}(10\text{^}(-8,9) + 10\text{^}(-9,1)) = -86,9 \text{ dBm} \quad \text{(B.5.27)}$$

where the noise floor of -91 dBm is coming from a thermal noise of -104 dBm and an assumed noise figure of 13 dB. The expected minimum decodable input signal level can be computed as:

$$P_{decode} = P_{I+N} + SNR_{V2V} + IM = -84,4 \text{ dBm} + SNR_{V2V} \quad \text{(B.5.28)}$$

with SNR_{V2V} according to Table B.1 and the Implementation Margin (IM) assumed during LTE-V2X specification is 2,5 dB.

Table B.11 summarizes the expected decode signal strength for different MCSs with the requirements given by the ITS-G5 decode signal strength. Here, it is observed that the delta between the 3GPP LTE-V2X in-band blocking requirement and existing AACR requirements in ETSI EN 302 571 [i.1] varies depending on the selected MCS.

Table B.11: Comparison of LTE-V2X and ITS-G5 signal strength needed to decode packets, for alternate adjacent channel interference with -47dBm for different MCSs

Modulation	Coding rate	ITS-G5 decodable signal strength (dBm)	LTE-V2X Expected decodable signal strength (dBm)	Delta
BPSK	1/2	-79	Not supported	
BPSK	3/4	-78	Not supported	
QPSK	1/2	-76	-85,6	9,6
QPSK	3/4	-74	-81,5	7,5
16-QAM	1/2	-71	-79,1	8,1
16-QAM	3/4	-67	-74,3	7,3
64-QAM	2/3	-63	Not supported	
64-QAM	3/4	-62	Not supported	

Using the definition of the ITS-G5 and LTE-V2X configurations from Table B.6 and Table B.7, the following Figure B.4 provides a comparison of ITS-G5 (blue circles) and LTE-V2X (black rectangles) decodable signal strengths for AACR tests from Table B.10 and Table B.11 respectively. For ITS-G5, the decodable signal strength originating from enhanced AACR requirements is also provided (green circles, 10 dB more stringent than the normal values for AACR). A linear fitting is performed for these three series, and is displayed in dotted lines of the corresponding color.

In addition, another series has been created by adapting the ITS-G5 values, by using the effective data rates based on 1 ms packets (from Table 5) shown with the red pentagons, with a curve fitting in the shape of $y = 10\log_{10}\left(2^{\frac{\bar{R}_{\text{eff Tx}}}{4}\frac{1}{[MBit/s]}} - 1\right) - X\,dB$, based on the sensitivity Equation (5.3.1). The best value of X is found to be 75,7, leading to the curve fitting formulas (B.5.28)and (B.5.29):

$$y = 10\log_{10}\left(2^{\frac{\bar{R}_{\text{eff Tx}}}{4}\frac{1}{[MBit/s]}} - 1\right) - 75{,}7\,dB \qquad \text{(B.5.29)}$$

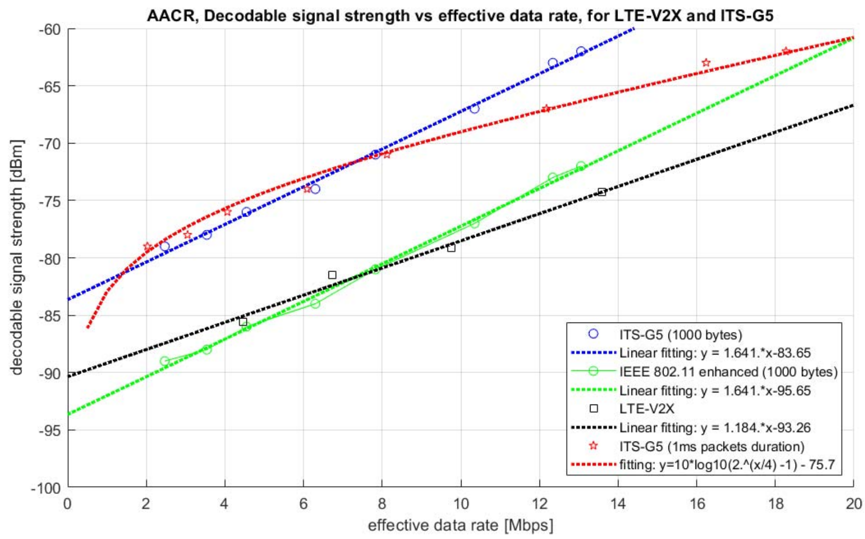

Figure B.4: Comparison of ITS-G5 and LTE-V2X decodable signal strengths for AACR tests, with signal of interest 6 dB above the sensitivity limit

It can be observed that:

- The first three series have the shape of a straight line (thus linear fitting is reasonable).
- The IEEE 802.11p enhanced and LTE-V2X values are fairly close.

- When plotting the ITS-G5 AACR values entries (y-axis) against the effective throughput using 1 ms packet (red pentagon stars), a change in shape is noticed, and the fitting $y = 10\log_{10}\left(2^{\frac{\bar{R}_{\text{eff Tx}}}{4}\frac{1}{[MBit/s]}} - 1\right) - 75{,}7\ dB$ is proposed.

From Equation (B.5.29), an 'empirical' AACR requirement formula can be derived as:

$$AACR_{req} = -(\text{fitting})dBm + P_{interf} + 2{,}5\ dB) \qquad \text{(B.5.30)}$$

Replacing (fitting) by formula (B.5.29), it can be derived that:

$$AACR_{req} = -\left(10\log_{10}\left(2^{\frac{\bar{R}_{\text{eff Tx}}}{4}\frac{1}{[MBit/s]}} - 1\right) - 75{,}7\ dB\right)dBm + P_{interf} + 2{,}5\ dB)$$

$$AACR_{req} = -\left(10\log_{10}\left(2^{\frac{\bar{R}_{\text{eff Tx}}}{4}\frac{1}{[MBit/s]}} - 1\right) - 75{,}7\ dB\right)dBm - 47\text{dBm} + 2{,}5\ dB)$$

Finally leading to a possible 'empirical' AACR requirement formula (B.5.31):

$$AACR_{req} = -10\log_{10}\left(2^{\frac{\bar{R}_{\text{eff Tx}}}{4}\frac{1}{[MBit/s]}} - 1\right) + 31{,}2\ dB \qquad \text{(B.5.31)}$$

Annex C: 3GPP Configuration A.8.2 (ETSI TS 136 101)

ETSI TS 136 101 [i.4] defines V2X reference measurement channels in clause A.8.

Configuration A.8.2 teaches usage of one allocation of 50 RB (48 RB of PSSCH + 2 RB of PSCCH), with a transport block size of 3 496 bits (437 bytes), with QPSK modulation and a coding rate of approximately 1/3, corresponding to I_MCS 4, as shown with the below quoted italic text.

*"**Table A.8.2-1 Fixed Reference measurement channel for V2V receiver requirements***

Parameter	*Unit*	*Value*					
Channel bandwidth	*MHz*	*1.4*	*3*	*5*	*10*	*15*	*20*
Allocated resource blocks					*48*		*96*
Subcarriers per resource block					*12*		*12*
Packets per period					*1*		*1*
Modulation					*QPSK*		*QPSK*
Target Coding Rate					*1/3*		*1/3*
Transport Block Size					*3496*		*6968*
Transport block CRC	*Bits*				*24*		*24*
Number of Code Blocks per Sub-Frame					*1*		*2*
Maximum number of HARQ transmissions					*1*		*1*
Binary Channel Bits per subframe	*Bits*				*11520*		*23040*
Max. Throughput averaged over 1 period of 100ms	*kbps*				*34.96*		*69.68*
UE Category					*≥ 1*		*≥ 1*
Note 1: 2RBs allocated to SA transmission and 4 symbols allocated to RS. *Note 2: Throughput (in kbps) will depend on SA period configuration.* *Note 3: If more than one Code Block is present, an additional CRC sequence of L = 24 Bits is attached to each Code Block (otherwise L = 0 Bit).*							

"

Annex D: 3GPP Reference sensitivity level for V2X Communication (ETSI TS 136 521-1, clause 7.3G)

Extract from clause 7.3G of ETSI TS 136 521-1 [i.11] on Test Specification of Reference Sensitivity Level for V2X Communication, as shown below in italic text:

"7.3G Reference sensitivity level for V2X Communication

7.3G.0 Minimum conformance requirements

When UE is configured for E-UTRA V2X reception non-concurrent with E-UTRA uplink transmissions for E-UTRA V2X operating bands specified in Table 5.2G-1, the throughput shall be ≥ 95% of the maximum throughput of the reference measurement channels as specified in Annexes A.8.2 with parameters specified in Table 7.3G.0-1.

Table 7.3G.0-1: Reference sensitivity of E-UTRA V2X Bands (PC5)

Channel bandwidth							
E-UTRA V2X Band	1.4 MHz (dBm)	3 MHz (dBm)	5 MHz (dBm)	10 MHz (dBm)	15 MHz (dBm)	20 MHz (dBm)	Duplex Mode
47				-90.4		-87.5	HD
NOTE 1: Reference measurement channel is defined in A.8.2. NOTE 2: The signal power is specified per port.							

Table 7.3G.0-1a: Sidelink TX configuration for reference sensitivity of E-UTRA V2X Bands (PC5)

E-UTRA Band / Channel bandwidth / NRB / Duplex mode							
E-UTRA V2X Band	1.4 MHz	3 MHz	5 MHz	10 MHz	15 MHz	20 MHz	Duplex Mode
47				50		98	HD

"

[combination of V2X sidelink with Uu and multicarrier operation in Rel. 15 omitted here]

The normative reference for this requirement is ETSI TS 136 101 [i.4], clause 7.3.1G.

"7.3G.1 Reference sensitivity level for V2X Communication / Non-concurrent with E-UTRA uplink transmissions

7.3G.1.1 Test purpose

Verify that UE receives V2X Communication physical channels data with a given average throughput under conditions of low signal level and ideal propagation.

7.3G.1.2 Test applicability

This test case applies to all types of UE that support V2X Sidelink Communication and Band 47.

7.3G.1.3 Minimum conformance requirements

The minimum conformance requirements are defined in clause 7.3G.0.

7.3G.1.4 Test description

7.3G.1.4.1 Initial conditions

Initial conditions are a set of test configurations the UE needs to be tested in and the steps for the SS to take with the UE to reach the correct measurement state.

The initial test configurations consist of environmental conditions, test frequencies, and channel bandwidths based on E-UTRA operating bands specified in table 5.4.2G.1-1. All of these configurations shall be tested with applicable test parameters for each channel bandwidth, and are shown in table 7.3G.1.4.1-1. The details of the V2X reference measurement channels (RMCs) are specified in Annex A.8.3 and the GNSS configuration in TS 36.508 [7] subclause 4.11.

Table 7.3G.1.4.1-1: Test Configuration Table

Initial Conditions		
Test Environment as specified in TS 36.508[7] subclause 4.1	Normal, TL/VL, TL/VH, TH/VL, TH/VH	
Test Frequencies as specified in TS 36.508 [7] subclause 4.3.1	Mid range	
Test Channel Bandwidths as specified in TS 36.508 [7] subclause 4.3.1	Lowest, Highest	
Test Parameters for Channel Bandwidths		
	V2X Configuration to Transmit	
Ch BW	Modulation	RB allocation
10MHz	QPSK	48
20MHz	QPSK	96

1. Connect the SS to the UE antenna connectors and connect the GNSS simulator to the UE GNSS RX antenna connector as shown in TS 36.508 [7] Annex A, Figure A.92.

2. The parameter settings for the V2X sidelink transmission over PC5 are pre-configured according to TS 36.508 [7] subclause 4.10.1. Message content exceptions are defined in clause 7.3G.1.4.3.

3. The V2X reference measurement channel is set according to Table 7.3G.1.4.1-1.

3a. The GNSS simulator is configured for Scenario #1: static in Geographical area #1, as defined in TS36.508 [7] Table 4.11.2-2. Geographical area #1 is also pre-configured in the UE.

4. Propagation conditions are set according to Annex B.0.

5. Ensure the UE is in State 5A-V2X in Receive Mode according to TS 36.508 [7] clause 4.5.9. Message content exceptions are defined in clause 7.3G.1.4.3.

6. Trigger the UE to reset UTC time. (NOTE: The UTC time reset may be performed by MMI or AT command (+CUTCR).)

7. The GNSS simulator is triggered to start step 1 of Scenario #1 to simulate a location in the centre of Geographical area #1. Wait for the UE to acquire the GNSS signal and start to transmit.

7.3G.1.4.2 Test procedure

1. The UE starts to perform the V2X sidelink communication according to SL-V2X-Preconfiguration and to schedule the V2X RMC according to Table 7.3G.1.4.1-1.

2. Set the signal level of V2X to the appropriate REFSENS value defined in Table 7.3 G.1.3-1.

3. Measure the average throughput for a duration sufficient to achieve statistical significance according to Annex G.2.

7.3G.1.4.3 Message contents

Message contents are according to TS 36.508 [7] subclause 4.10.

7.3G.1.5 Test requirements

When UE is configured for E-UTRA V2X reception non-concurrent with E-UTRA uplink transmissions for E-UTRA V2X operating bands specified in Table 5.2G-1, the throughput shall be ≥ 95% of the maximum throughput of the reference measurement channels as specified in Annexes A.8.2 with parameters specified in Table 7.3G.1.5-1.

Table 7.3G.1.5-1: Reference sensitivity

Channel bandwidth							
E-UTRA V2X Band	***1.4 MHz (dBm)***	***3 MHz (dBm)***	***5 MHz (dBm)***	***10 MHz (dBm)***	***15 MHz (dBm)***	***20 MHz (dBm)***	***Duplex Mode***
47				*-89*		*-86.1*	*TDD*
NOTE 1: Reference measurement channel is defined in A.8.2. *NOTE 2: The signal power is specified per port.*							

"

Annex E: Sensitivity vs required throughput

In general, receiver sensitivity can be described as:

Sensitivity = Thermal_Noise_Density + 10 x Log10(bandwidth) + NF + IM + SNR_dB (dBm) (E.1)

With:

- Thermal_Noise_Density denoting the thermal noise in dBm/Hz;
- bandwidth the transmission bandwidth in Hz;
- NF the noise figure in dB;
- IM the implementation margin in dB;
- SNR_dB the signal-to-noise level in dB required for a specific throughput.

At room temperature it can be assumed that Thermal_Noise_Density ≈ -174 dBm/Hz; assuming 10 MHz transmission bandwidth it can be derived that 10 x Log10(10 MHz) = 70 dBHz and the noise figure and implementation margin according to ETSI EN 302 571 [i.1], clause 4.2.8.1, are 10 dB and 5 dB, respectively. Using those values, Equation (E.1) can be re-written as:

Sensitivity = -89 dBm + SNR_dB (E.2)

A simple empirical expression to link the sensitivity requirement values defined in ETSI EN 302 571 [i.1] with the effective throughput of ITS-G5 is provided with following Equation (E.3):

Sensitivity = -88 + Effective_Throughput_in_Mpbs (dBm) (E.3)

Equation (E.3) can thus be viewed as defining the noise floor, including thermal noise, noise figure and implementation margin, plus an additional SNR term in dB which defines the SNR required for a specific throughput.

By applying a curve fitting technique for ITS-G5 with a packet length of 1 000 bytes on the MCS and sensitivity level from Table 9 of ETSI EN 302 571 [i.1], the following correspondence can be observed:

SNR_dB = 1 dB x (Effective_Throughput/1 Mbps) (E.4)

In other words, to achieve 1 Mbps increase in effective throughput a 1 dB increase in SNR is required.

NOTE: The required throughput is assumed to be 100 % of the maximum throughput for (E.4) to facilitate a good comparison with Equation (E.3).

Combining Equations (E.2) and (E.4) yields the result Equation (E.3), where the deviation of 1 dB for the noise power results mainly from the difference in the assumed packet length.

It is thus possible to derive an empirical relationship between the receiver sensitivity level and the SNR required for a given throughput based on the noise figure and implementation margin.

Annex F: Generic receiver sensitivity limit

F.1 Introduction

Testing of receiver sensitivity requires a precise specification of the test setup, the test method as well as the specification of testable limits. This annex describes a possible minimum set of parameters that specify receiver sensitivity testing of an arbitrary radio communication systems that use QAM or similar modulation schemes on multiple OFDM carriers. It is shown that for a certain test method and setup the sensitivity limit can be defined analytically from signal theory and physics based on system performance parameters independent of the number of carriers, the carrier spacing, and the exact MCS.

These system performance parameters are the duration of the transmitted data packets as function of the effective data rate.

This leads to receiver sensitivity limits based on common criteria for different communication systems, i.e. it implicitly defines the radio parameters of the receiver.

F.2 Receiver errors

F.2.1 Reason for detection errors in digital receivers

The reason for detection errors of a received signal is noise generated in the receiver circuit (Noise picked up by the receiver antenna can usually be neglected in a test setup). Noise in the receiver circuit stems from thermal noise in resistors or other noise sources in semiconductor devices (e.g. shot noise). Usually, these noise sources are summarized in what is called the *Noise Figure* (*NF*) of a receiver.

F.2.2 Thermal noise

The lower bound of the receiver noise is given by the Johnson-Nyquist thermal noise power generated in any resistor:

$$N = K_B \times T \times B. \tag{F.2.1}$$

Where N is the noise power measured in Watt, K_B = 1,38 10^{-23} J/K is the Boltzmann constant, T is the temperature measured in Kelvin and B is the bandwidth measured in Hertz.

For a bandwidth of B = 10 MHz and a temperature of T = 300 K the Johnson-Nyquist noise power level results to:

$$N_{dBm} = 10 \times log_{10}(N) + 30\ dB = -103{,}8\ dBm \tag{F.2.2}$$

This noise adds to any signal in the receiver. Since its amplitude statistics follows a gaussian distribution and it has equal power density over all frequencies it is called *Additive White Gaussian Noise* (AWGN). The noise power level N is twice the square of the standard deviation σ of the gaussian noise amplitude density function [i.8]:

$$N = 2\ \sigma^2 \tag{F.2.3}$$

F.2.3 Receiver error probability in an AWGN radio channel

Most digital communication systems use phase and amplitude modulated subcarriers with equal frequency spacing within the used bandwidth (Orthogonal Frequency Division Multiplexing - OFDM).

For each digital symbol k the modulated subcarrier $S_k(t)$ is a sinusoidal signal in time t with angular frequency ω described by its amplitude A_k and its phase φ_k:

$$S_k(t) = A_k \times \sin(\omega \times t + \varphi_k) \tag{F.2.4}$$

For further analysis of the signal detection error probability only the signal constellation in the signal space is relevant. In signal space the Symbol S_k is mapped to a pointer with the length A_k and the angle φ_k relative to the x-axis. This mapping can be seen as a snapshot of $S_k(t)$ at time $t = 0$ in the imaginary plane (mapping to a complex signal).

For explanation of the receiver error probability a simple Phase Shift Keying (PSK) subcarrier signal with 4 symbols (4-PSK) is used as an example. This signal is only phase modulated with constant amplitude $A_k = A$ and 4 distinct phase values $\varphi_k = \{¼ \pi, ¾ \pi, -¼ \pi, -¾ \pi\}$. Figure F.1 shows the signal constellation of the 4-PSK modulation, where the distance d between the Symbols S_k is normalized to one.

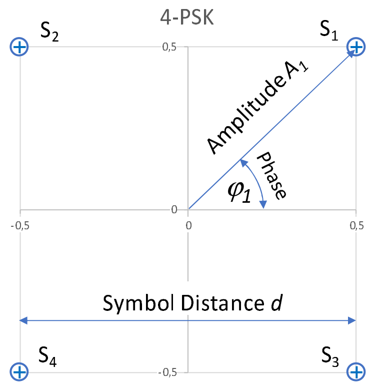

Figure F.1: Signal constellation of a 4-PSK signal in signal space

The receiver uses a discriminator to distinct the data symbols. Since the noise amplitude is a stochastic process with a gaussian distribution of the amplitude values, the symbol error rate is given by the probability that the added noise causes the sum signal to cross the discriminator threshold to another symbol. Hence, when the amplitude of the added noise in direction of another symbol is smaller than halve of the symbol distance d the symbol is still decoded correctly. Since the symbols in the 4-PSK constellation are arranged in a square (therefore this modulation is often called Quadrature Phase Shift Keying QPSK) the discriminator region is given by two thresholds. For a correct reception the noisy received signal should stay within the discriminator region and hence within both thresholds. The probability for this is the product of the probabilities for staying within each of the thresholds.

Since the amplitude density function of the noise has gaussian shape with a standard deviation of σ, the error probability P_E for a single sided discriminator threshold is given by the Q-function:

$$P_E = Q(z) = \frac{1}{\sqrt{2\pi}} \int_z^{\infty} e^{\frac{-x^2}{2}} dx \qquad \text{(F.2.5)}$$

Where z is defined by the discriminator threshold, which is halve the symbol distance d, and by the standard deviation σ of the noise amplitude, which is the square root of the noise power level (see Equation (F.2.3)):

$$z = \frac{d}{2\,\sigma} = \frac{d}{\sqrt{2\,N}} \qquad \text{(F.2.6)}$$

NOTE: Instead of the Q-function also the complementary error function *erfc(x)* can be used to calculate the error probability:

$$P_E = Q(z) = \frac{1}{2}\, erfc\left(\frac{z}{\sqrt{2}}\right) \qquad \text{(F.2.7)}$$

Coming back to the 4-PSK example, the probability that the noisy signal at the discriminator stays within one e.g. the horizontal single sided discriminator threshold is $1\text{-}P_E$. The same holds for the second vertical discriminator threshold, and hence the probability for staying within both thresholds is the product of these two probabilities $(1\text{-}P_E)\times(1\text{-}P_E) = (1\text{-}P_E)^2$. Since this probability is the same for all symbols, finally the AWGN error probability for a 4-PSK modulation results to:

$$P_{E\ 4PSK} = 1 - \left(1 - Q\left(\frac{d}{\sqrt{2\,N}}\right)\right)^2 \qquad \text{(F.2.8)}$$

F.2.4 Receiver error probability for QAM signals in an AWGN radio channel

The aim of this annex is to find an analytic function that defines a receiver sensitivity limit based on signal theory and physics. It is proposed to use the properties of different Quadrature Amplitude Modulation (QAM) configurations as basis for this limit function, since QAM is commonly used in digital communication systems because of its high spectral efficiency and flexible implementation properties.

QAM can be seen as an extension of 4-PSK. All symbols are arranged in a quadratic grid with constant mesh width around a 4-PSK constellation. Figure F.2 shows the signal constellation of the commonly used 16-QAM that adds 12 more transmit symbols around the 4-PSK constellation. The more transmit symbols in a signal constellation the more bits can be carried by one symbol. Hence, when using the same coding rate, the binary logarithm of the number of transmit symbols is proportional to the data rate. The error probability in a receiver strongly depends on the symbol distance *d*. Therefore, when increasing the number of transmit symbols, the amplitude of the received signal needs to be increased to keep the received signal error probability constant. Or in other words, the receiver sensitivity for a constant symbol detection error rate decreases. Additionally, the "inner" symbols need 4 discriminator thresholds to confine their discriminator region, further increasing the error probability for these symbols.

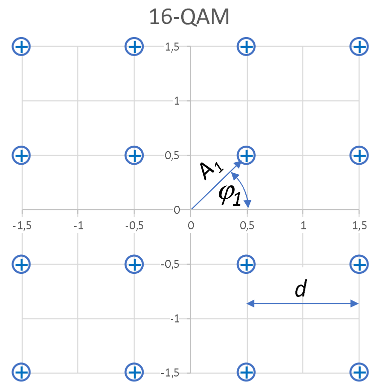

Figure F.2: Signal constellation of a 16-QAM signal in the signal space normalized to a symbol distance *d* = 1

To study different QAM configurations, a parameter *n* is introduced that describes the order of the QAM. *n* is defined in such a way that *n* = 0 corresponds to a 4-PSK, *n* = 1 a 16-QAM, *n* = 2 a 36-QAM (which is normally not used), *n* = 3 a 64-QAM, and so on.

NOTE 1: In literature the order of a QAM is often characterized by *M*. Where $M \times M = 4 \times (n + 1)^2$ is the number of QAM symbols in the constellation.

To calculate the error probability, the symbols of a QAM can be categorized into three types:

1) 4 corner symbols with two single-sided discriminator thresholds;

2) $8 \times n$ edge symbols with one single-sided and one double-sided discriminator threshold;

3) $4 \times n^2$ inner symbols with two double-sided discriminator thresholds.

The Q-function gives the probability of exceeding a single-sided threshold. Since the Gauss-function is symmetric around zero, the probability to exceed a symmetric double-sided threshold is twice the probability of exceeding the corresponding single-sided threshold. Taking this into account and assuming all $4 \times (n + 1)^2$ QAM symbols to be used with the same probability, the average QAM symbol error is:

$$P_{E\ QAM}(n) = \frac{1}{(1+n)^2}\left[1-(1-P_E)^2 + 2n \times \left(1-(1-P_E)(1-2\,P_E)\right) + n^2 \times \left(1-(1-2\,P_E)^2\right)\right] \quad \text{(F.2.9)}$$

$$P_{E\ QAM}(n) = P_E \times \frac{2\,(1+2n)}{1+n} - P_E^2 \times \left(\frac{1+2n}{1+n}\right)^2 \quad \text{(F.2.10)}$$

The receiver sensitivity is always defined for a certain symbol error probability $P_{E\,QAM}$. The definition of a generic receiver sensitivity limit should therefore also be based on a given constant symbol error probability $P_{E\,QAM}$. From Equation (F.2.10) the error probability P_E can be calculated for this given $P_{E\,QAM}$:

$$P_E(n) = \frac{1+n}{1+2n}\left(1 - \sqrt{1 - P_{E\,QAM}}\right) \qquad \text{(F.2.11)}$$

From Equation (F.2.5) and Equation (F.2.6) follows:

$$P_E(n) = Q\left(\frac{d(n)}{2\,\sigma}\right) \qquad \text{(F.2.12)}$$

Applying the inverse Q-function to PE leads to the relation between the discriminator threshold value $d/2$ and the standard deviation σ of the noise amplitude density function:

$$Q^{-1}(P_E(n)) = \frac{d(n)}{2\,\sigma} \qquad \text{(F.2.13)}$$

NOTE 2: The inverse Q-function can also be expressed by the inverse complementary error function:

$$Q^{-1}(P_E(n)) = \sqrt{2}\; erfc^{-1}(2\,P_E(n)) \qquad \text{(F.2.14)}$$

This result can be used to calculate the necessary signal power level at the receiver input to achieve the given symbol error probability $P_{E\,QAM}$ for a given noise power level σ^2. For the calculation of the average received signal power level it is assumed that all symbols are transmitted with equal probability. The average sensitivity power level P_{rs} can then be calculated according to:

$$P_{rs}(n) = \frac{d_{(n)}^2}{(1+n)^2}\sum_{l=0}^{n}\sum_{k=0}^{n}\left[\left(\frac{1}{2}+l\right)^2 + \left(\frac{1}{2}+k\right)^2\right] \qquad \text{(F.2.15)}$$

After some calculation (see Annex G) this sum can be transformed into an equivalent analytic function:

$$P_{rs}(n) = \frac{1}{6}(1+2\,n)\,(3+2\,n)\,d_{(n)}^2 \qquad \text{(F.2.16)}$$

With this result, Equation (F.2.6), Equation (F.2.11) and Equation (F.2.13) can be used to calculate the necessary signal to noise ratio (SNR) for a given symbol error probability $P_{E\,QAM}$ and QAM order n:

$$SNR(n) = \frac{P_{rs}(n)}{N} = \frac{1}{3}(1+2\,n)\,(3+2\,n)\left(Q^{-1}\left(\frac{1+n}{1+2n}\left(1 - \sqrt{1 - P_{E\,QAM}}\right)\right)\right)^2 \qquad \text{(F.2.17)}$$

$$SNR_{dB} = 10\log(SNR) = 10\log\left(2\,\frac{P_{rs}(n)}{d_{(n)}^2}\right) + 20\,log\left(Q^{-1}(P_E(n))\right) \qquad \text{(F.2.18)}$$

The first term in Equation (F.2.18) corresponds to the influence of the QAM order (number of symbols) on the symbol distance, the second term accounts for the influence of the symbol constellation on the error probability. It will be shown in clause F.4.3.4 that for a small symbol error probability P_{EQAM} the second term is almost constant over the QAM order n.

Table F.1 shows the properties of different QAM configurations. The nominal data rate relative to a 2-PSK modulation is proportional to the number of bits per symbol $lb(4\times(n+1)^2)$ (see also Equation (F.3.3) and Equation (F.4.7)).

Table F.1: Different QAM configurations and their properties

n	transmit symbols	relative data rate	Symbol error probability $P_{E\,QAM}$	SNR
0	4	2	$2\,P_E - P_E^{\,2}$	$\left(Q^{-1}\left(1-\sqrt{1-P_{E\,QAM}}\right)\right)^2$
1	16	4	$3\,P_E - 9/4\,P_E^{\,2}$	$5\left(Q^{-1}\left(\frac{2}{3}\left(1-\sqrt{1-P_{E\,QAM}}\right)\right)\right)^2$
2	36	5,17	$10/3\,P_E - 25/9\,P_E^{\,2}$	$\frac{35}{3}\left(Q^{-1}\left(\frac{3}{5}\left(1-\sqrt{1-P_{E\,QAM}}\right)\right)\right)^2$
3	64	6	$7/2\,P_E - 49/16\,P_E^{\,2}$	$21\left(Q^{-1}\left(\frac{4}{7}\left(1-\sqrt{1-P_{E\,QAM}}\right)\right)\right)^2$

NOTE 3: For small symbol error probabilities ($P_{E\,QAM}$<<1) the result can be simplified assuming following relations:

$$P_E^{\,2} \approx 0 \text{ and } 1-\sqrt{1-P_{E\,QAM}} \approx \frac{1}{2}P_{E\,QAM} \qquad \text{(F.2.19)}$$

F.3 Analysis of the sensitivity limits given in IEEE 802.11

F.3.1 2-PSK modulation

In addition to different QAM configurations, IEEE 802.11-2016 [i.3] also uses 2-PSK modulation for low data rates. In this simple case the symbol distance is twice the signal amplitude *A*. Hence, the discriminator threshold is *A* and the symbol error results to:

$$P_{E\,2PSK} = Q\left(A\sqrt{\frac{2}{N}}\right) \qquad \text{(F.3.1)}$$

From this the signal to noise ratio can be calculated:

$$SNR_{2PSK\,dB} = 20\log\left(\frac{1}{\sqrt{2}}Q^{-1}(P_{E\,2PSK})\right) \qquad \text{(F.3.2)}$$

F.3.2 Coding rate

IEEE 802.11-2016 [i.3] foresees to use a convolutional encoder to add code redundancy. This reduces the symbol error probability. But the nominal data rate is also reduced by a factor called *Coding Rate* (*CR*).

The reduction of the symbol error probability is characterized by the *coding gain* (γ_c), which is the SNR improvement due to code redundancy for a given symbol error probability at a certain effective data rate. The coding gain depends mainly on the encoder type. Since the same convolutional encoder polynomials are used for all coding rates in IEEE 802.11-2016 [i.3], the coding gain for a certain QAM order is approximately proportional to the reciprocal of the coding rate - i.e. the coding increases the hamming distance between the QAM symbols by a factor that is approximately proportional to the coding rate (see Figure F.4).

For a certain data rate, the convolutional encoder used in IEEE 802.11-2016 [i.3] exhibits a coding gain of around 7 dB - almost independently of the coding rate [i.8] and [i.9]. This approximation is even better than the hamming distance approximation, but it works only for data rates starting at 12 MBit/s and higher (see Figure F.3).

F.3.3 Symbol error rate

IEEE 802.11-2016 [i.3] specifies the receiver sensitivity at different data rates for a data packet size of n_{Byte} = 1 000 Byte at a packet error ratio of *PER* = 0,1. To link this *PER* to the QAM symbol error probability $P_{E\,QAM}$ for QAM order *n*, also taking the coding rate *CR* into account, the number of data Symbols $n_{Symbols}$ can be calculated from the number of Bits $n_{Bits} = 8 \times n_{Byte}$ in the data packet:

$$n_{Bits/Symbol} = lb(4 \times (n+1)^2) \quad \text{(F.3.3)}$$

$$n_{Symbols} = \frac{n_{Bits}}{CR \times n_{Bits/Symbol}} \quad \text{(F.3.4)}$$

Under the assumption that the coding reduces the QAM symbol error probability $P_{E\,QAM}$ by a factor equal to the coding rate *CR*, the probability of a correct frame reception (1-*PER*) is the probability that all symbols ($n_{Symbols}$) are correctly received:

$$1 - PER = \left(1 - CR \times P_{E\,QAM}\right)^{n_{Symbols}} \quad \text{(F.3.5)}$$

From this the QAM symbol error probability $P_{E\,QAM}$ corresponding to a given packet error rate *PER* can be calculated:

$$P_{E\,QAM} = \frac{1}{CR}\left(1 - \sqrt[n_{Symbols}]{1 - PER}\right) \quad \text{(F.3.6)}$$

F.3.4 Model of the IEEE 802.11 sensitivity limits

ITS-G5 uses the Modulation and Coding Schemes (MCS) which are listed in Table F.2 together with the corresponding data rates and sensitivity limits. The necessary SNR for these modulation schemes can be calculated with Equation (F.2.18) (SNR_{dB}) and the QAM symbol error probability resulting from Equation (F.3.6) ($P_{E\,QAM}$), using the *PER* coming from the IEEE receiver sensitivity test specification as described in clause F.3.3.

As can be seen in Figure F.3 the IEEE 802.11 receiver sensitivity limit lies almost exactly 15 dB above the thermal noise N_{dBm} plus the SNR_{dB} from Equation (F.2.18) for a pure QAM without encoding (*CR* = 1). This stems from the fact that the coding gain of the convolutional encoder used by ITS-G5 is almost constant for all coding rates [i.8] and [i.9]. Hence, the receiver sensitivity values can be approximated from the SNR obtained from a QAM without encoding by applying a fixed coding gain factor independently of the coding rate (see also clause F.3.2).

Since ITS-G5 uses not only QAM but also 2-PSK with a coding rate of ½, the lowest data rate that can be achieved is 3 MBit/s. Even for QAM, the receiver sensitivities for data rates below 12 MBit/s cannot be modelled by just using a constant factor to the QAM SNR with a *CR* = 1. To calculate the SNR for 2-PSK modulated signals, Equation (F.3.2) can be used. To account for the fact that the coding rate increases the hamming distance between the QAM symbols the coding gain $\gamma_{c\,dB}$ for the convolutional encoder can be estimated by:

$$\gamma_{c\,dB}(CR) = 10 \times log\left(\frac{2}{CR}\right) \quad \text{(F.3.7)}$$

NOTE: This is a rough generic estimation of the coding gain. It does not take puncturing or properties of specific coder implementations into account. Therefore, this approximation might not be applicable over the whole coding rate range.

With this coding gain $\gamma_{c\,dB}$ and a noise figure of NF_{dB} = 15 dB in addition to the thermal noise N_{dBm} the IEEE 802.11 receiver sensitivity limit P_{RSens} can be modelled for different MCS:

$$P_{RSens} = N_{dBm} + SNR + NF_{dB} - \gamma_{c\,dB}(CR) \quad \text{(F.3.8)}$$

Where *SNR* is the signal to noise ratio of the corresponding modulation scheme of ITS-G5 (2-PSK, 4-PSK, 16-QAM, or 64-QAM) from Equation (F.2.18) or Equation (F.3.2). A comparison of this model with the receiver sensitivity vales as specified in IEEE 802.11-2016 [i.3] (see Table F.2) is shown in Figure F.4.

Table F.2: Sensitivity limits given in IEEE 802.11-2016 [i.3] for different modulation and coding schemes for 10 MHz channel bandwidth

Nominal data rate (MBit/s)	Modulation	Coding rate	Sensitivity limit (dBm)
3	2-PSK	1/2	-85
4,5	2-PSK	3/4	-84
6	4-PSK	1/2	-82
9	4-PSK	3/4	-80
12	16-QAM	1/2	-77
18	16-QAM	3/4	-73
24	64-QAM	2/3	-69
27	64-QAM	3/4	-68

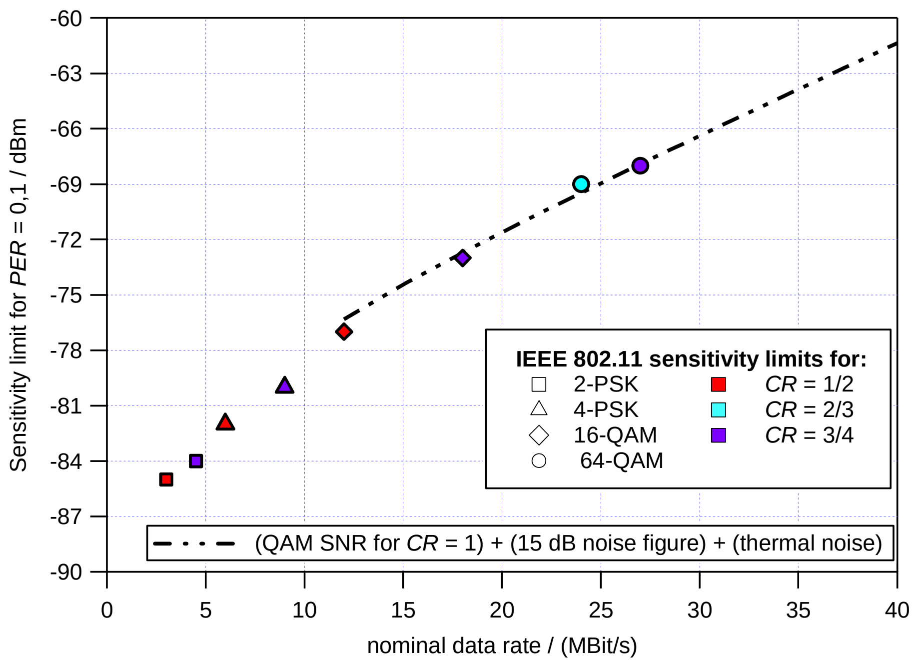

Figure F.3: IEEE receiver sensitivity limits for 1 000 Byte packets and PER = 0,1 as function of the nominal data rate and sensitivity from QAM SNR plus fixed noise figure

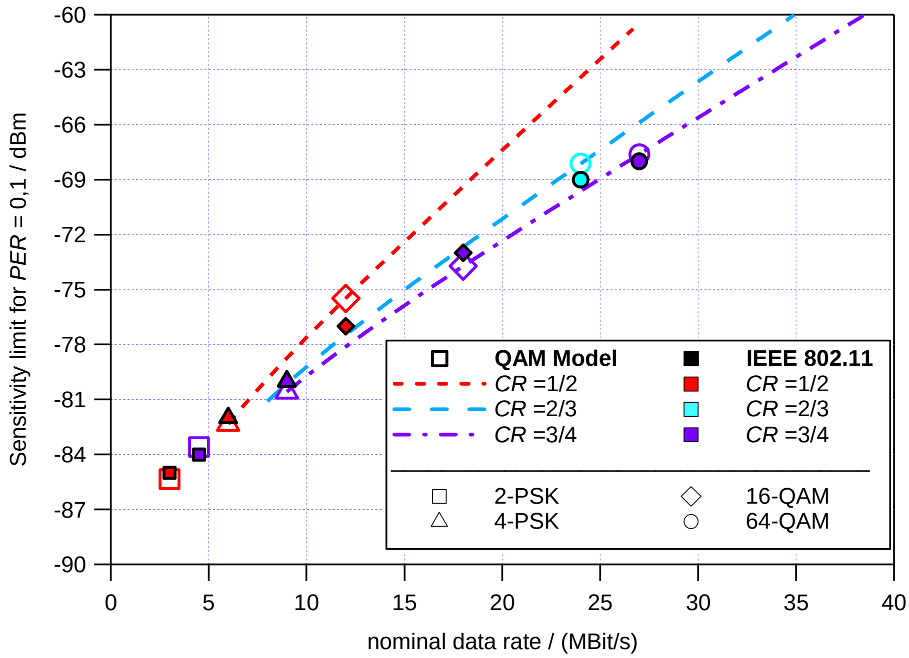

Figure F.4: IEEE receiver sensitivity limits for 1 000 Byte packets and PER = 0,1 as function of the nominal data rate, plus a calculation based on the QAM error statistics and a hamming distance approximation of the coding gain

F.4 Generic receiver sensitivity limits

F.4.1 Generic setup and procedure for conformance tests

To test whether the receiver sensitivity conforms generic limits, requires a common test setup and test procedure applicable to any communication system. For different communication systems there are only a few parameters that can be easily measured, like the power density function of the transmit spectrum, the effective data rate, and the transmit power function over time. Therefore, test specifications for certain communication systems usually require the device manufacturer to declare the configuration of the test setup (e.g. MCS) or specify parameters as *PER* or the number of data bytes to be used. For a certain communication technology all possible configuration combinations can be listed together with the applicable limits to assess the according test result. This is not possible for generic limits applicable to any communication technology, and test specifications in harmonised standards should not be based on parameters that are declared by the device manufacturer.

For a certain MCS the receiver sensitivity is usually defined as the power level at the receiver where the *PER* of a packet with a defined size exceeds a defined limit. Except the power level at the receiver, none of these parameters can be directly measured. An alternative possibility to define the receiver sensitivity is to base it on the effective data rate, that can be measured for any communication system. The effective data rate can either be defined to be the number of correctly received data bits in relation to a sufficiently long averaging duration, or in relation to the actually measured duration the transmitter was active. The first definition assumes that data can be transmitted at a maximum channel on-time ratio allowed by the MAC. The second definition also works when the transmitter is sometimes idle, not transmitting at the highest possible channel on-time ratio, but in this case the transmit power function over time needs to be determined.

Since every data communication system needs to transfer management data between the communication devices, the effective data rate is always lower than the data rate at which the communication data is transferred. This overhead depends on the communication technology and the duration of the transmission of the data packet, since the overhead has usually in average a constant duration for each data packet, while the data packet duration depends on the MCS and the number of transferred bits. One possibility to keep the relative overhead time in relation to the data transmission time constant, is to adjust the number of data bits dependent on the MCS. This allows to define a receiver sensitivity limit that assumes a constant time ratio between data communication and management information. I.e. the number of effective data symbols, taking the coding rate into account, is kept constant independent of the MCS.

F.4.2 A conformance test procedure for V2X communication systems

A conformance test procedure for V2X communication systems can be based on following assumptions that can be achieved in a test mode for all MCS of common communication systems:

a) The signal modulation performs equivalent or better than QAM.

b) Defined constant packet duration.

c) Constant average management overhead time.

d) Constant packet error ratio (*PER*) for different MCS.

ad b) and c)
A constant packet duration for different MCS keeps the number of symbols independent of the MCS when the management overhead in time is constant. A constant packet duration can be measured with a spectrum analyser in Zero Span mode. No special measurement equipment is necessary to check the correctness of the test configuration. There is no need for long lasting measurements of the power level statistics over time.

ad d)
Constant *PER* simplifies the calculation of the effective data rate R_{eff}, that results from the nominal data rate R_{MCS}, the management time overhead t_m and the packet duration t_p according to:

$$R_{eff} = R_{MCS} \times (1 - PER) \times \frac{t_p - t_m}{t_p} \quad \text{(F.4.1)}$$

Under the assumption that the PER, t_p and t_m are constant for all MCS, the effective data rate R_{eff} is proportional to the nominal data rate defined by the MCS. This makes it possible to measure the *PER* by measuring the effective data rate and gives the justification why the receiver sensitivity can be specified by the effective data rate R_{eff}.

F.4.3 Proposed generic receiver sensitivity limit

F.4.3.1 Starting point - packet duration and packet error ratio

The idea behind this proposed generic sensitivity limit is, that it should be based on the existing receiver properties as specified in IEEE 802.11-2016 [i.3], but that it should be applicable to any other technology. And that it should be possible to measure all relevant communication parameters without special test equipment. This also implies that declarations of the device manufacturer concerning the test configuration are not necessary.

In clause F.4.2 the assumptions a) to d) are given:

- Assumption a) holds for IEEE 802.11 devices, since they use QAM.
- To define a reproducible test procedure for any technology, the packet duration t_p should have a fixed defined value, what can be achieved by IEEE 802.11 based communication systems, fulfilling assumption b).
- For IEEE 802.11 devices, the average management overhead time t_m for an ITS-G5 packet consists of the AIFS time, the average contention time, the preamble and the MAC header (assumption c).
- Under assumption d), for a *PER* independent of the MCS, the symbol error rate *SER* can be estimated for QAM signals as function of the *CR* only, independent of the modulation order.

F.4.3.2 Management overhead time

The MAC timing parameter are specified in ETSI EN 302 663 [i.2]. The preamble and the MAC header last together 40 µs. The AIFS time and the average contention time depend on the Access Category (AC). For CAM messages the Access Category *Best Effort* (AC_BE) is used. For this AC AIFS = 110 µs, and the contention time can vary between 0 µs and is 15 × 13 µs. Hence, in average the contention time is 97,5 µs. And the total management overhead time is tm = 40 + 110 + 97,5 = 247,5 µs.

F.4.3.3 Mapping of the IEEE 802.11 receiver sensitivity limits to the effective data rate

With Equation (F.4.1), the IEEE 802.11 receiver sensitivity limits can be mapped to an effective data rate. The *PER* is given by IEEE 802.11 to be *PER* = 0,1. The total management overhead time for CAMs as calculated in clause F.4.3.2 is t_m = 247,5 µs. It is proposed to set t_p = 1 ms, since this value can be handled by all V2X communication technologies known at the time of preparation of the present document. The nominal data rate values R_{MCS} for different coding schemes are defined in ETSI EN 302 663 [i.2] and are listed in Table F.2 together with the corresponding sensitivity limits.

Table F.3 lists the effective data rates for different IEEE 802.11 MCS and a constant frame duration of t_p = 1 ms.

NOTE: These values are different from the effective data rates when using a constant number of data bytes as specified in the IEEE 802.11 receiver sensitivity test specification.

Table F.3: Mapping of IEEE 802.11 nominal data rates to effective data rates and corresponding receiver sensitivity values for a fixed packet duration of t_p = 1 ms

Nominal data rate (MBit/s)	Effective data rate (MBit/s)	Sensitivity limit (dBm)
3	2,0	-85
4,5	3,0	-84
6	4,1	-82
9	6,1	-80
12	8,1	-77
18	12,2	-73
24	16,3	-69
27	18,3	-68

F.4.3.4 Generic receiver sensitivity limits based on IEEE 802.11

In clause F.3.4 it was shown how the sensitivity limit values given by IEEE 802.11-2016 [i.3] can be modelled based on signal theory.

IEEE 802.11-2016 [i.3] defines the *PER* for the receiver sensitivity measurement to be 0,1. For QAM signals the symbol error probability $P_{E\,QAM}$ from Equation (F.3.6) estimates the symbol error rate for a given *PER* and a given number of symbols $n_{Symbols}$. The duration of a symbol t_s is 8 µs (see ETSI EN 302 663 [i.2]), the packet duration is set to t_p= 1 ms, and preamble plus the MAC header last for t_h = 40 µs. Hence, the number of symbols in NC = 48 subcarriers is $n_{Symbols}$ = 48 × (1 000 - 40)/8 = 5 760. And the symbol error rate for different coding rates *CR* results to:

$$P_{E\,QAM} = \frac{1}{CR}\left(1 - \sqrt[5\,760]{1 - 0{,}1}\right) = \frac{1{,}83 \times 10^{-5}}{CR} \qquad \text{(F.4.2)}$$

Taking the simplifications for small symbol error probabilities into account Equation (F.2.18) can be rewritten to:

$$SNR_{dB} = 10 \log\left(\frac{1}{3}(1 + 2\,n)\,(3 + 2\,n)\right) + 20\,log\left(Q^{-1}\left(\frac{1}{2}\frac{1+n}{1+2n}P_{E\,QAM}\right)\right) \qquad \text{(F.4.3)}$$

Substituting the $P_{E\,QAM}$ value from Equation (F.4.2) results to:

$$SNR_{dB} = 10 \log\left(\frac{1}{3}(1 + 2\,n)\,(3 + 2\,n)\right) + 20\,log\left(Q^{-1}\left(\frac{1+n}{1+2n}\frac{1{,}83 \times 10^{-5}}{2 \times CR}\right)\right) \qquad \text{(F.4.4)}$$

For a fixed *CR* = 1 the second term varies for *n* between 0 to ∞ by 0,30 dB:

$$20\,log\left(Q^{-1}\left(\frac{1{,}83 \times 10^{-5}}{2}\right)\right) = 12{,}64\,dB \qquad \text{(F.4.5)}$$

$$20\,log\left(Q^{-1}\left(\frac{1{,}83 \times 10^{-5}}{4}\right)\right) = 12{,}94\,dB \qquad \text{(F.4.6)}$$

Therefore, this term can be set to a fixed value of 12,7 dB to model the sensitivity limit values with a fixed coding rate close to one.

To plot the receiver sensitivity limit over the effective data rate R_{eff} that can be measured, first the relation between n and the nominal data rate *RMCS* that is proportional to the number of bits per symbol needs to be known:

$$R_{MCS} = R_0 \times lb(4 \times (n+1)^2) \quad \text{(F.4.7)}$$

Where for ITS-G5 the initial data rate R_0 for a $CR = 1$ and 2-PSK modulation is 6 MBit/s.

From Equation (F.4.7) n can be expressed as function of *RMCS*:

$$n = \frac{1}{2} \times 2^{\frac{R_{MCS}}{2 \times R_0}} - 1 \quad \text{(F.4.8)}$$

With this, an analytic extension of the SNR function to data rates below R_0 is possible that can model the behaviour of a convolutional encoder as described in clause F.3.2.

Substituting this result into Equation (F.4.4) and setting the 2^{nd} term to 12,7 dB results in:

$$SNR_{dB} = 10 \log_{10}\left(\frac{1}{3}\left(2^{\frac{R_{MCS}}{2 \times R_0}} - 1\right)\left(2^{\frac{R_{MCS}}{2 \times R_0}} + 1\right)\right) + 12{,}7\ dB \quad \text{(F.4.9)}$$

What can be further simplified to:

$$SNR_{dB} = 10 \log_{10}\left(2^{\frac{R_{MCS}}{R_0}} - 1\right) + 8\ dB \quad \text{(F.4.10)}$$

With Equation (F.4.1) R_{MCS} can be written as function of R_{eff}:

$$SNR_{dB} = 10 \log_{10}\left(2^{\frac{R_{eff} \times t_p}{R_0 \times (1-PER) \times (t_p - t_m)}} - 1\right) + 8\ dB \quad \text{(F.4.11)}$$

Since most of these values are constant, SNR_{dB} can be further simplified to:

$$SNR_{dB} = 10 \log_{10}\left(2^{\frac{R_{eff}}{4} \frac{1}{[MBit/s]}} - 1\right) + 8\ dB \quad \text{(F.4.12)}$$

With the thermal noise of N_{dBm} = -103,8 dBm and a noise plus coding margin of NC_{dB} = 14,5 dB the receiver sensitivity can be modelled as follows to match the limits given by IEEE 802.11-2016 [i.3]:

$$P_{GSens} = N_{dBm} + NC_{dB} + SNR_{dB} = 10 \log_{10}\left(2^{\frac{R_{eff}}{4} \frac{1}{[MBit/s]}} - 1\right) - 81{,}3\ dB \quad \text{(F.4.13)}$$

Figure F.5 shows a comparison between the generic sensitivity limit for 1 ms data packets according to Equation (F.4.13) and the IEEE sensitivity limits mapped to the corresponding effective data rate from Table F.3.

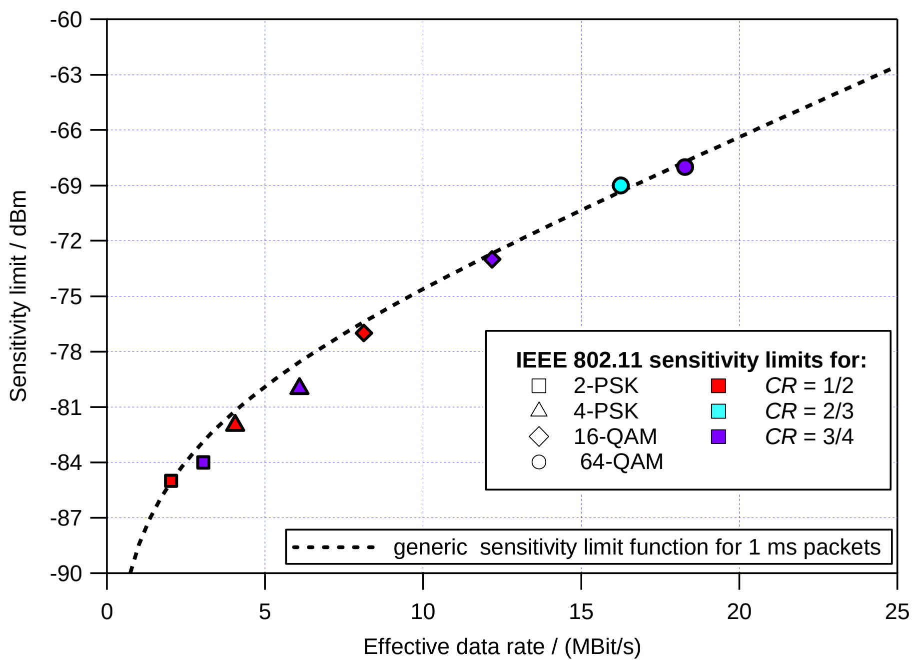

Figure F.5: Generic sensitivity limit for 1 ms packet duration over the effective data rate

F.4.3.5 Comparison of ITS-G5 and LTE-V2X sensitivity values with the generic receiver sensitivity limit

In clause F.4.3.4 some simplifications were done to obtain a generic sensitivity limit for OFDM based communication systems that matches to the sensitivity limit given in IEEE 802.11-2016 [i.3]. This clause shows how this limit fits to the sensitivity values resulting from an exact calculation based on the properties of ITS-G5 and of LTE-V2X as listed in Table F.4. It is expected that a future NR-V2X radio will have a packet duration of 0,5 ms and that the use of two consecutive packets fits to the proposed test specification described in Annex H.

Table F.4: ITS-G5 and LTE-V2X physical layer parameters for the sensitivity calculation

Parameter	ITS-G5	LTE-V2X
Thermal noise power level N_{dBm}	-103,8 dBm	-103,8 dBm
Noise figure NF_{dB}	15 dB	15 dB
Packet Error Rate *PER*	0,1	0,1
Packet duration t_p	1 000 µs	1 000 µs
Number of OFDM data carriers (*NC*) = Number of symbols per symbol duration (excluding management data e.g. SCI)	48	48 Resource Blocks × 12 subcarriers = 576
symbol duration (t_s)	8 µs	1/14 ms = 71,4 µs
Reference data rate $Rref = 2 \times R0$ for OFDM order n = 0 (4-PSK) and *CR* = 1 (2 Bit/Symbol)	48 Symbols × 2 Bit / (8 µs) = = 12 MBit/s	576 Symbols × 2 Bit ×14 / (1 ms) = = 16,128 MBit/s
Typical average management overhead time t_m (see also clause F.4.3.2)	Header duration (t_h) + AIFS + *CWmin* / 2 × Slot Time = = (40 + 110 + 15/2 × 13) µs= = 247,5 µs	1/14 ms × (4 reference signals + + 2 management slots) = = 3/7 ms = 428,57 µs
Symbols $n_{Symbols}$ in a packet with duration t_p	$NC \times (t_p - t_h) / t_s$ = 5 760	$NC \times 8$ data time slots = 4 608

For *CR* = 1 and a coding gain $\gamma_{c\,dB}$ = 0 dB Equation (F.2.17), Equation (F.3.6), and Equation (F.3.8) can be combined to calculate the receiver sensitivity $P_{S\,dBm}$ for different OFDM orders n:

$$P_{S\,dBm} = N_{dBm} + NF_{dB} + 10 \times \log_{10}\left(\frac{1}{3}(1+2\,n)\,(3+2\,n)\,\left(Q^{-1}\left(\frac{1+n}{1+2n}\left(1-\sqrt[2\times n_{Symbols}]{1-PER}\right)\right)\right)^2\right) \quad \text{(F.4.14)}$$

The nominal data rate R_{MCS} for CR = 1 is used as parameter to calculate n for Equation F.4.14 (see also Equation (F.4.8)).

$$n = \frac{1}{2} \times 2^{\frac{R_{MCS}}{R_{ref}}} - 1 \qquad \text{(F.4.15)}$$

The corresponding effective data rate results from the nominal data rate *RMCS*, the packet error rate *PER*, the packet duration t_p, and the management overhead time *tm* as shown in Equation (F.4.1).

Figure F.6 and Figure F.7 show a comparison of the results from Equation F.4.14 for *CR* = 1 and of the coding gain estimation from Equation (F.3.8) for different other *CRs* for ITS-G5 and LTE-V2X based on the parameters from Table F.4 and the sensitivity limits presented in the previous clauses. As can be seen, the difference between the generic limit for the receiver sensitivity and the calculated sensitivity values for LTE-V2X and for ITS-G5 can be neglected. Hence, the proposed limit works fine for different OFDM configurations.

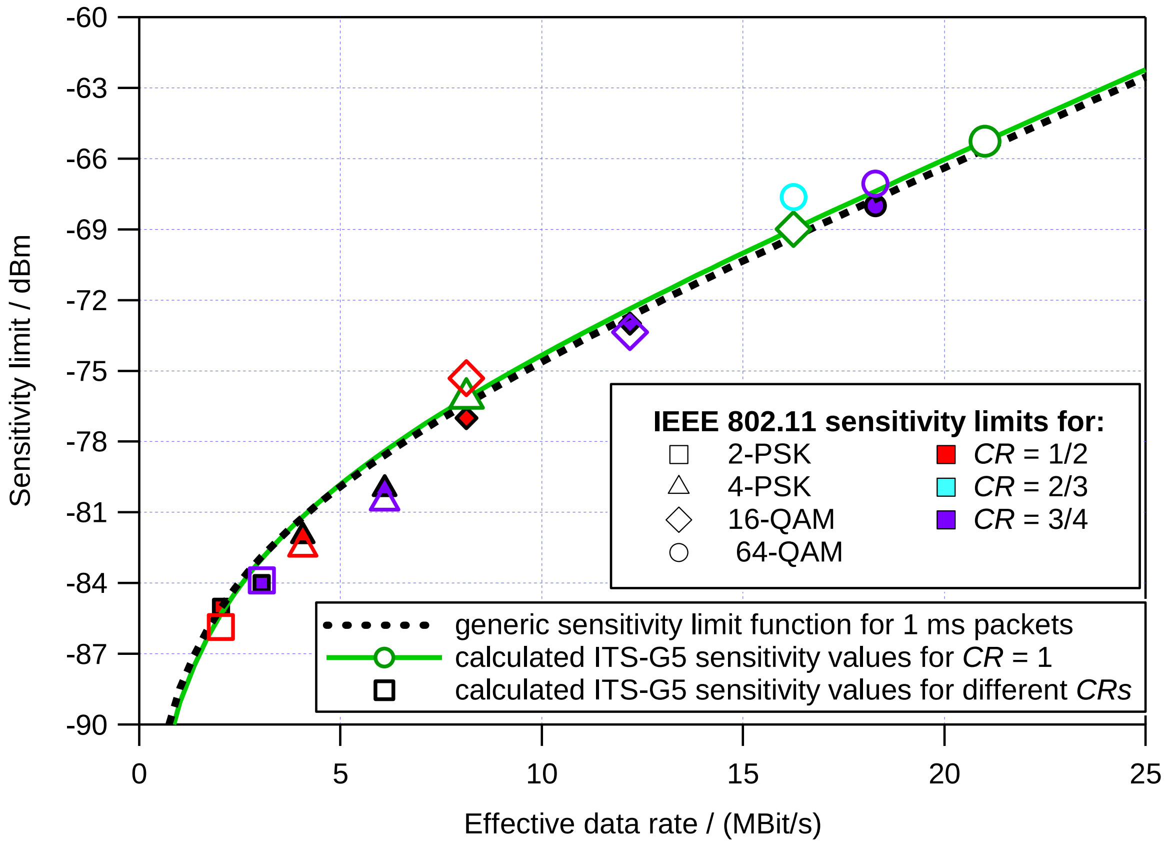

Figure F.6: Comparison of calculated ITS-G5 sensitivity values with the proposed generic sensitivity limit and with the limits from IEEE 802.11-2016 [i.3]

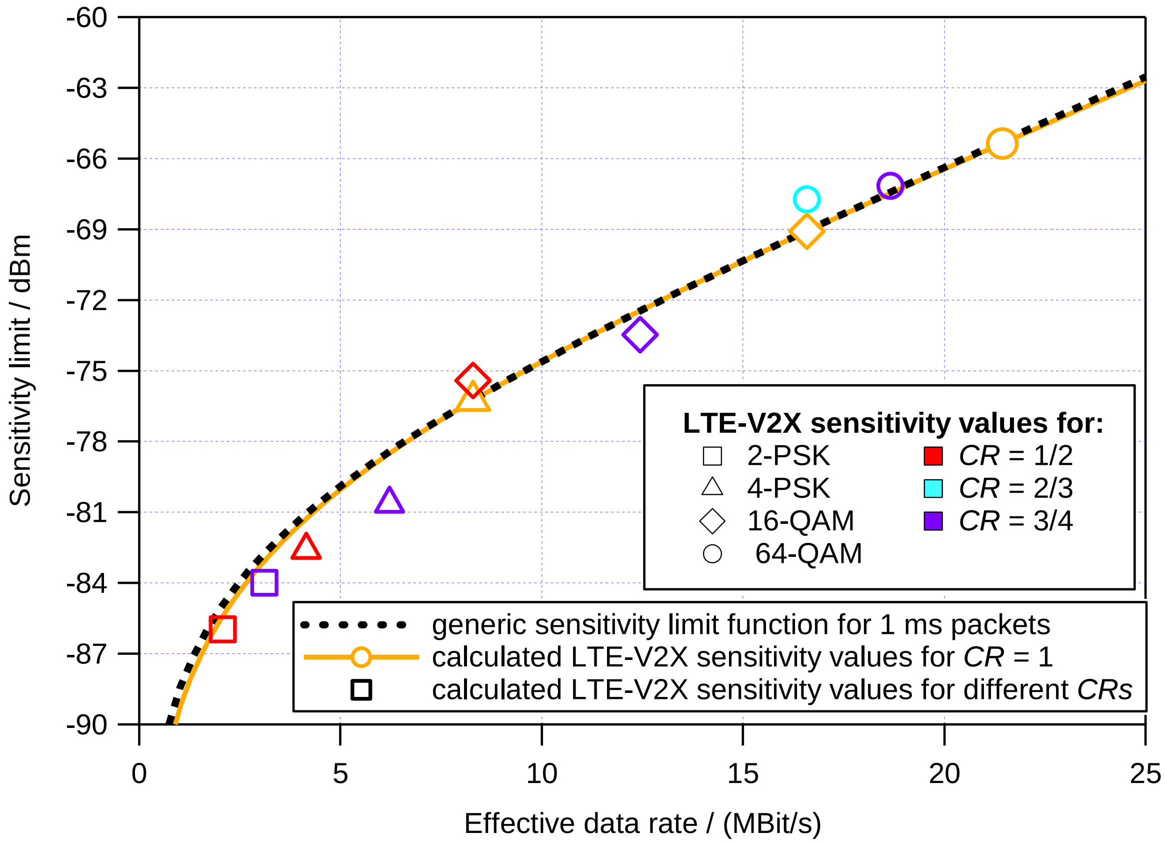

Figure F.7: Comparison of calculated LTE-V2X sensitivity values with the proposed generic sensitivity limit

Annex G: Average power level calculation

Equation (F.2.15) can also be written as:

$$P_{rs}(n) = \frac{d_{(n)}^2}{(1+n)^2}\left(\sum_{l=0}^{n}\sum_{k=0}^{n}\left[\left(\tfrac{1}{2}+l\right)^2\right] + \sum_{l=0}^{n}\sum_{k=0}^{n}\left[\left(\tfrac{1}{2}+k\right)^2\right]\right) \quad \text{(G.1)}$$

This can be simplified to:

$$P_{rs}(n) = \frac{2 \times d_{(n)}^2}{1+n}\left(\sum_{m=0}^{n}\left[\left(\tfrac{1}{2}+m\right)^2\right]\right) \quad \text{(G.2)}$$

Thus, an analytic function f(n) solving Equation (G.2) would fulfil:

$$\mathrm{f}(n) = \sum_{m=0}^{n}\left[\left(\tfrac{1}{2}+m\right)^2\right] \forall\, n \in \mathbb{N} \quad \text{(G.3)}$$

Such a function also fulfils:

$$\Delta\mathrm{f}(n) = \mathrm{f}(n+1) - \mathrm{f}(n) = \left(\sum_{m=0}^{n+1}\left[\left(\tfrac{1}{2}+m\right)^2\right] - \sum_{m=0}^{n}\left[\left(\tfrac{1}{2}+m\right)^2\right]\right) \forall\, n \in \mathbb{N} = \left(\tfrac{3}{2}+n\right)^2 \quad \text{(G.4)}$$

From this it gets obvious, that when an analytic function f(n) exists, it is a polynomial in n. Therefore, following ansatz can be used to solve the problem by finding the coefficients A, B, C, and D.

$$\mathrm{f}(n) = A \times n^3 + B \times n^2 + C \times n + D \quad \text{(G.5)}$$

Since analytic functions are infinitely differentiable, the coefficients can be obtained from the derivatives of Δf(n):

$$\Delta\mathrm{f}(n) = \mathrm{f}(n+1) - \mathrm{f}(n) = \left(\tfrac{3}{2}+n\right)^2 = A \times (3\,n^2 + 3\,n + 1) + B \times (2\,n+1) + C \quad \text{(G.6)}$$

$$\Delta\mathrm{f}\,'(n) = \mathrm{f}\,'(n+1) - \mathrm{f}\,'(n) = 2 \times \left(\tfrac{3}{2}+n\right) = 3 \times A \times (2\,n+1) + 2 \times B \quad \text{(G.7)}$$

$$\Delta\mathrm{f}\,''(n) = \mathrm{f}\,''(n+1) - \mathrm{f}\,''(n) = 2 = 6 \times A \quad \text{(G.8)}$$

From this follows: $A = \frac{1}{3}$, $B = 1$, and $C = \frac{11}{12}$. The coefficient D follows from $D = \mathrm{f}(0) = \frac{1}{4}$.

Factorizing the resulting polynomial leads to:

$$\mathrm{f}(n) = \frac{1}{12}(n+1)(2\,n+1)(2\,n+3) \quad \text{(G.9)}$$

Equation (F.2.16) can be obtained from combining Equation (G.9) with Equation (G.3) and Equation (G.2). The result can be seen in Figure G.1, which shows a comparison between Equation (F.2.15) and Equation (F.2.16) normalized for a symbol distance of d = 1.

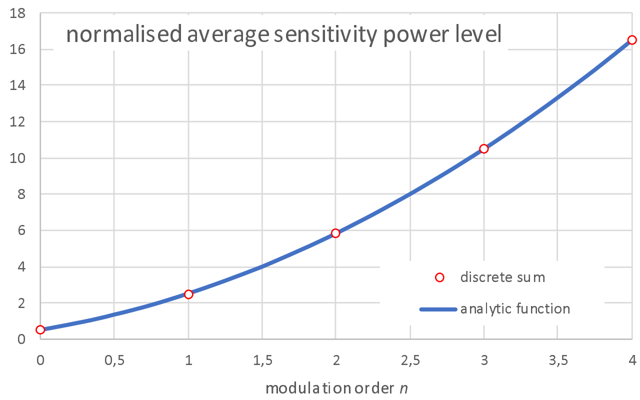

Figure G.1: Comparison between the discrete calculation of the normalized average sensitivity power level (Equation (F.2.15)) and the analytic function (Equation (F.2.16))

Annex H: Generic receiver sensitivity test specification

H.1 Test equipment for the sensitivity test

A generic receiver sensitivity test can be performed by use of a spectrum analyser and a bit rate measurement. To provide adjustable input signal power levels, variable attenuators (e.g. a step attenuator) are used, and their Dynamic range should be greater or equal than 30 dB. The maximum step size should be 1 dB.

The test transmitter should be able to continuously transmit data packets with a reproducible constant average channel on-time ratio $\bar{T}_{onR}$:

$$\bar{T}_{onR} = \frac{T_{on}}{T_{on}+T_{off}} \quad \text{(H.1.1)}$$

and with reproducible constant average efficient data rates $\overline{R_{\text{eff OnR Tx}}}$, defined by the total number of transmitted Bits $n_{total\ Bits\ Tx}$ over the test duration T_{test}.

$$\bar{R}_{\text{eff OnR Tx}} = \bar{T}_{onR} \cdot \bar{R}_{\text{eff Tx}} = \frac{n_{total\,Bits\,Tx}}{T_{test}} \quad \text{(H.1.2)}$$

T_{on} and T_{off} are the total time spans where the test transmitter is transmitting or respectively not transmitting during the whole test duration $T_{test} = T_{on} + T_{off}$. $\bar{R}_{eff\,Tx}$ would be the average effective data rate for a continuous transmission of data packets over the whole test duration T_{test} in case $\bar{T}_{onR}$ would be one. $\bar{R}_{eff\,Tx}$ is given by the ratio of the average number of bits per packet $\bar{n}_{Bits}$ and the average packet duration $\bar{t}_b$ and can be determined from the ratio between the measured average efficient data rate $\bar{R}_{eff\,OnR\ Tx}$ and the average channel on-time ratio $\bar{T}_{onR}$.

$$\bar{R}_{eff\ Tx} = \frac{\bar{n}_{Bits}}{\bar{t}_b} = \frac{\overline{\bar{R}_{\text{eff OnR Tx}}}}{\bar{T}_{onR}} \quad \text{(H.1.3)}$$

The duration of each single data packet transmitted within the test duration T_{test} should be set to be as close as possible to 1 ms for technologies that can adjust packet duration, while technologies that have fixed packet size use multiple subframes to get to as close as possible to 1 ms, including management overhead as defined for example in clause F.4.3.2.

It is essential for the measurement accuracy that $\bar{R}_{eff\,OnR\ Tx}$ and $\bar{T}_{onR}$ are not changing while performing the test execution for a certain operational data rate.

H.2 Test setup for the sensitivity test

For a single Rx antenna port test, an overview schematic of the test setup for the receiver sensitivity test is shown in Figure H.1.

For a multiple Rx antenna ports test (Rx_1 to Rx_k), an overview schematic of the test setup for the receiver sensitivity test is shown in Figure H.2.

NOTE: For a DUT with multiple Rx antenna ports, one way of testing is to test each receive antenna separately (as per a single Rx antenna port test description) and another way is to test with multiple antennas (as per multiple Rx antenna ports test description). If each receive antenna is tested separately, the unused RX port should be 50 ohms terminated.

The test should be performed in two steps:

1) **Test preparation:** For a single Rx antenna port test, a spectrum analyser is connected to the step attenuator instead of the DUT to calibrate the Rx power level and to measure the channel on-time ratio of the test transmitter.

   For a multiple Rx antenna ports test, in case a power splitter is used as shown on Figure H.2, a spectrum analyser is connected to each output of the power splitter instead of the DUT to calibrate the Rx power level.

The absolute value of the Rx power level deviation between the different outputs of the power slitter should be less than 1 dB.

2) **Test execution:** The DUT is connected to the step attenuator and the effective bit rate is measured for different settings of the step attenuator.

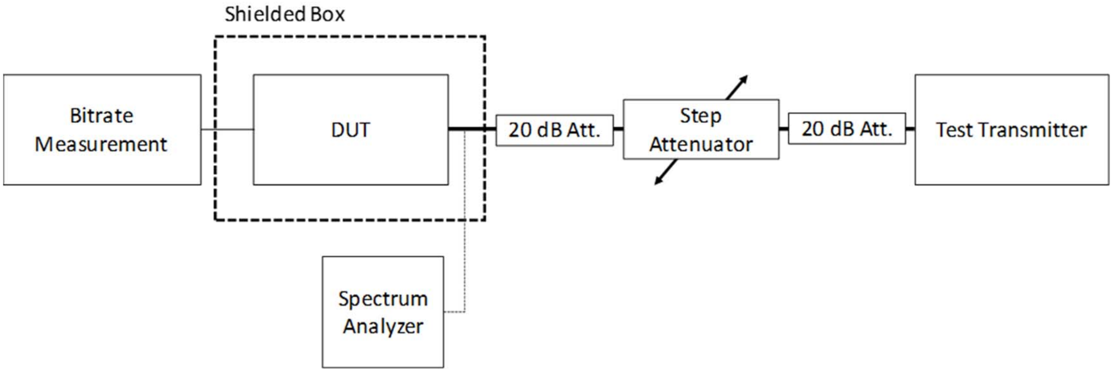

Figure H.1: Test setup for a single Rx antenna port test

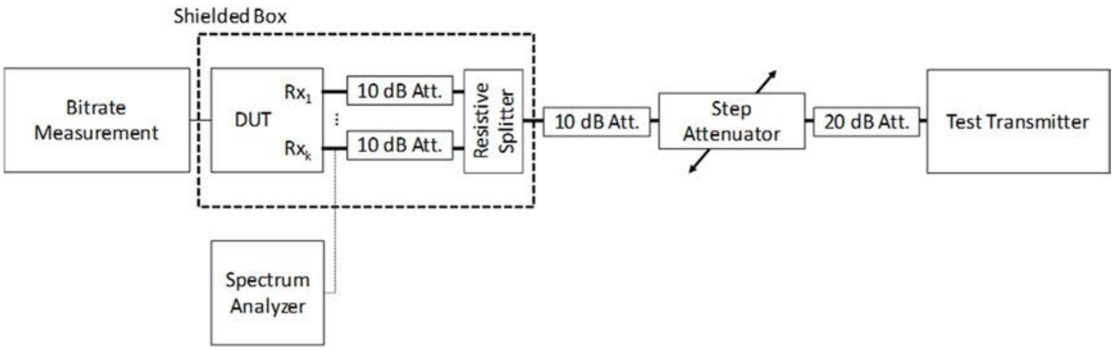

Figure H.2: Test setup for a multiple Rx antenna ports (Rx_1 to Rx_k) test

H.3 Generic receiver sensitivity test

H.3.1 Sensitivity test preparation

For calibration a Spectrum Analyser (SA) or an equivalent test system is connected to the test setup instead of the DUT. The measurements should be performed with the rms detector of the SA. The output power level of the test transmitter is set to such a value that at full attenuation of the step attenuator the input peak power level to the DUT is below -90 dBm. To calibrate the input power level at the DUT the step attenuator is set to the lowest attenuation step and the power level at the DUT connector is measured.

The SA can be used in zero-span mode to measure whether the channel on-time ratio and the packet duration of the test transmitter are within the specified limits. Alternatively, the channel on-time ratio can also be evaluated from the ratio between the average and the peak power level determined for the whole measurement duration.

The ambient temperature for the test is set to 300 K (27 °C).

H.3.2 Sensitivity test execution

For the sensitivity test the DUT is connected to the test setup as shown in Figure H.1, or to the test setup as shown in Figure H.2 in case the DUT has multiple antenna receiver inputs and such receive antenna ports are tested simultaneously with a power splitter yielding identical power to each antenna input.

The sensitivity test should be done for a channel bandwidth of 10 MHz, and one or several data rates test-points may be defined.

For each data rate test-point, and for all receiver inputs in case the DUT has multiple receiver inputs that are tested separately, the test execution can be done following the below steps:

1) Determine by use of the total received Bits $n_{total\ Bits\ Rx}$ during the test duration T_{test} the average received effective data rate $\bar{R}_{eff\ OnR\ Rx} = \frac{n_{total\ Bits\ Rx}}{T_{test}}$ under ideal reception conditions well above the sensitivity limit at each and every antenna input. And determine the average channel on-time ratio $\overline{T_{\text{OnR}}}$ by measuring the ratio between the active and the idle channel state.

   - To check whether the test time duration T_{test} is chosen sufficiently long, following steps can be performed:

     ▪ Determine $\bar{R}_{\text{eff OnR Rx}}(T_{test})$ for the full test time duration T_{test}.

     ▪ Reduce the test time duration to its half $\frac{T_{test}}{2}$.

     ▪ Determine $\bar{R}_{\text{eff OnR Rx}}\left(\frac{T_{test}}{2}\right)$.

     ▪ The test time is long enough when:

$$0{,}99 \leq \frac{\bar{R}_{\text{eff OnR Rx}}(T_{test})}{\bar{R}_{\text{eff OnR Rx}}\left(\frac{T_{test}}{2}\right)} \leq 1{,}01 \qquad \text{(H.3.1)}$$

   - To check whether the receive power level P_{Rx} at each and every antenna input of the DUT is chosen sufficiently high for ideal reception conditions, following steps can be performed:

     ▪ Determine $\bar{R}_{eff\ OnR\ Rx}(P_{Rx})$ for the full receive power level P_{Rx}.

     ▪ Reduce the receive power level by 6 dB to $P_{Rx} - 6\ dB$.

     ▪ Determine $\bar{R}_{\text{eff OnR Rx}}(P_{Rx} - 6\ dB)$.

     ▪ The receive power level is high enough when:

$$0{,}99 \leq \frac{\bar{R}_{\text{eff OnR Rx}}(P_{Rx})}{\bar{R}_{\text{eff OnR Rx}}(P_{Rx} - 6\ dB)} \leq 1{,}01 \qquad \text{(H.3.2)}$$

   - If the test time duration T_{test} is chosen sufficiently long and the receive power level is sufficiently high, then the average transmitted effective data rate $\bar{R}_{eff\ OnR\ Tx}$ can be treated as equal to the measured $\bar{R}_{eff\ OnR\ Rx}$.

2) Reduce the signal power level at the DUT receiver input(s) until the measured average effective data rate $\bar{R}_{eff\ OnR\ Rx}$ reaches 90 % of $\bar{R}_{eff\ OnR\ Tx}$ as determined in step 1) under ideal conditions. I.e. the packet error rate reaches *PER* = 0,1. When adjusting the signal power level stepwise, the power level step where the packet error rate is just below 0,1 (*PER* ≤ 0,1) should be used for the data rate measurement in the next step.

3) Determine the average transmitted effective data rate for a hypothetical continuous transmission $\bar{R}_{eff\ Tx} = \frac{\bar{R}_{eff\ OnR\ Tx}}{\bar{T}_{onR}}$ and calculate the sensitivity limit P_{Sens} from Equation (5.3.1), using this average effective data rate $\bar{R}_{eff\ Tx} = R_{eff}$ for *PER* = 0,1.

4) If the signal power level at the receiver inputs is below this sensitivity limit P_{Sens} , then the test is passed.

Annex I: Generic receiver selectivity test specification

I.1 Test equipment for selectivity tests

A generic receiver selectivity test in form of Adjacent Channel Rejection (ACR) and Alternate Adjacent Channel Rejection (AACR) can be performed by use of a spectrum analyser and a bit rate measurement. To provide adjustable input signal power levels, variable attenuators (e.g. a step attenuator) are used, and their Dynamic range should be greater or equal than 30 dB. The maximum step size should be 1 dB.

The test transmitter should be able to continuously transmit data packets with a reproducible constant average channel on-time ratio $\bar{T}_{onR}$:

$$\bar{T}_{onR} = \frac{T_{on}}{T_{on}+T_{off}} \quad \text{(I.1.1)}$$

and with reproducible constant average efficient data rates $\overline{R_{\text{eff OnR Tx}}}$, defined by the total number of transmitted Bits $n_{total\ Bits\ Tx}$ over the test duration T_{test}.

$$\bar{R}_{\text{eff OnR Tx}} = \bar{T}_{onR} \cdot \bar{R}_{\text{eff Tx}} = \frac{n_{total\ Bits\ Tx}}{T_{test}} \quad \text{(I.1.2)}$$

T_{on} and T_{off} are the total time spans where the test transmitter is transmitting or respectively not transmitting during the whole test duration $T_{test} = T_{on} + T_{off}$. $\bar{R}_{eff\ Tx}$ would be the average effective data rate for a continuous transmission of data packets over the whole test duration T_{test} in case $\bar{T}_{onR}$ would be one. $\bar{R}_{eff\ Tx}$ is given by the ratio of the average number of bits per packet $\bar{n}_{Bits}$ and the average packet duration $\bar{t}_b$ and can be determined from the ratio between the measured average efficient data rate $\bar{R}_{eff\ OnR\ Tx}$ and the average channel on-time ratio $\bar{T}_{onR}$.

$$\bar{R}_{eff\ Tx} = \frac{\bar{n}_{Bits}}{\bar{t}_b} = \frac{\overline{\bar{R}_{\text{eff OnR Tx}}}}{\bar{T}_{onR}} \quad \text{(I.1.3)}$$

The duration of each single data packet transmitted within the test duration T_{test} should be set to be as close as possible to 1 ms for technologies that can adjust packet duration, while technologies that have fixed packet size use multiple subframes to get to as close as possible to 1 ms, including management overhead as defined for example in clause F.4.3.2.

It is essential for the measurement accuracy that $\bar{R}_{eff\ OnR\ Tx}$ and $\bar{T}_{onR}$ are not changing while performing the test execution for a certain operational data rate.

I.2 Test setup for selectivity tests

For a single Rx antenna port test, an overview schematic of the test setup for the receiver selectivity test is shown in Figure I.1.

For a multiple Rx antenna ports test (Rx_1 to Rx_k), an overview schematic of the test setup for the receiver selectivity test is shown in Figure I.2.

NOTE: For a DUT with multiple Rx antenna ports, one way of testing is to test each receive antenna separately (as per a single Rx antenna port test description) and another way is to test with multiple antennas (as per multiple Rx antenna ports test description). If each receive antenna is tested separately, the unused RX port should be 50 ohms terminated.

The test should be performed in two steps:

1) **Test preparation:** For a single Rx antenna port test, a spectrum analyser is connected to the resistive combiner instead of the DUT to calibrate the Rx power level and to measure the channel on-time ratio of the test transmitter.

   For a multiple Rx antenna ports test, in case a power splitter is used as shown on Figure I.2, a spectrum analyser is connected to each output of the power splitter instead of the DUT to calibrate the Rx power level.

The absolute value of the Rx power level deviation between the different outputs of the power slitter should be less than 1 dB.

2) **Test execution:** The DUT is connected to the step attenuator and the effective bit rate is measured for different settings of the step attenuator.

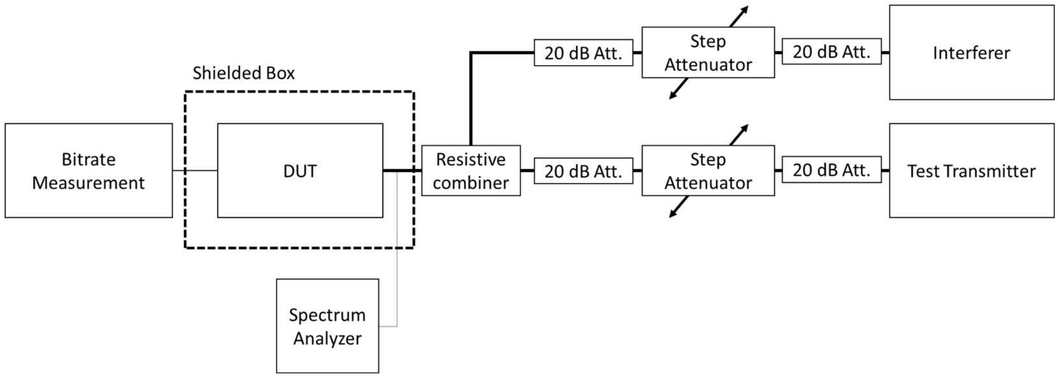

Figure I.1: Test setup for a single Rx antenna port test

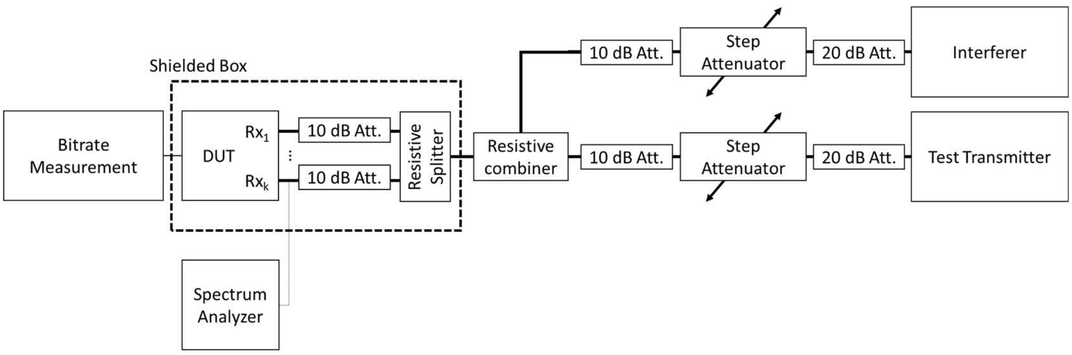

Figure I.2: Test setup for a multiple Rx antenna ports (Rx_1 to Rx_k) test

I.3 Generic receiver selectivity tests

I.3.1 Selectivity tests preparation

For calibration a Spectrum Analyser (SA) or an equivalent test system is connected to the test setup instead of the DUT. The measurements should be performed with the rms detector of the SA. The output power level of the test transmitter is set to such a value that at full attenuation of the step attenuator the input peak power level to the DUT is below -90 dBm. To calibrate the input power level at the DUT the step attenuator is set to the lowest attenuation step and the power level at the DUT connector is measured.

The SA can be used in zero-span mode to measure whether the channel on-time ratio and the packet duration of the test transmitter are within the specified limits. Alternatively, the channel on-time ratio can also be evaluated from the ratio between the average and the peak power level determined for the whole measurement duration.

For Adjacent Channel Rejection (ACR) test, the interfering signal is defined as a Continuous Wave (CW) sinusoid. The CW signal is frequency is set according to clause 6.3.4.

The ACR is measured by setting the desired signal's strength 6 dB above the effective data-rate-dependent sensitivity limit specified in clause 5.3, and raising the power of the interfering signal until 10 % PER is caused. The difference in power between the signals in the interfering channel and the desired channel is the corresponding adjacent channel rejection.

For Alternate Adjacent Channel Rejection (AACR) test, the interfering signal is defined as a Continuous Wave (CW) sinusoid. The CW signal frequency is set according to clause 6.3.4.

The nonadjacent channel rejection is measured by setting the desired signal's strength 6 dB above the rate-dependent sensitivity specified in clause 5.3, and raising the power of the interfering signal until a 10 % PER. The difference in power between the signals in the interfering channel and the desired channel is the corresponding nonadjacent channel rejection.

The ambient temperature for the test is set to 300 K (27 °C).

NOTE: It can be remarked that the ACR and AACR test procedures differ from the ones described in ETSI EN 302 571 [i.1] about the interferer nature: this document specifies usage of a Continuous Wave (CW) sinusoid signal while ETSI EN 302 571 specifies usage of an ITS-G5 transmitter. One possible effect due to this is a difference in amount of energy leakage from the interferer channel into the channel of the DUT. However, it should also be noted that the ETSI EN 302 571 [i.1] does not specify a specific amount of noise leakage, which means that a transmitter having minimal amount of out of channel emissions can be used for conducting such tests, which is arguably the case of professional test equipment (likely having a close to ideal transmit mask and sharp channel filters applied on the signal sent).

I.3.2 ACR and AACR Selectivity tests execution

For the selectivity tests the DUT is connected to the test setup as shown in Figure I.1, or to the test setup as shown in Figure I.2 in case the DUT has multiple antenna receiver inputs and such receive antenna ports are tested simultaneously with a power splitter yielding identical power to each antenna input.

The ACR and AACR selectivity tests use the same test execution procedure detailed below, and should be done one after the other, not simultaneously. The tests are done for a channel bandwidth of 10 MHz, and one or several data rates test-points may be defined.

For each data rate test-point, and for all receiver inputs in case the DUT has multiple receiver inputs that are tested separately, the test execution can be done following the below steps:

1) Determine by use of the total received Bits $n_{total\ Bits\ Rx}$ during the test duration T_{test} the average received effective data rate $\bar{R}_{eff\ OnR\ Rx} = \frac{n_{total\ Bits\ Rx}}{T_{test}}$ under ideal reception conditions well above the sensitivity limit at each and every antenna input. And determine the average channel on-time ratio $\overline{T_{\mathrm{OnR}}}$ by measuring the ratio between the active and the idle channel state.

   - To check whether the test time duration T_{test} is chosen sufficiently long, following steps can be performed:

     - Determine $\bar{R}_{\mathrm{eff\ OnR\ Rx}}(T_{test})$ for the full test time duration T_{test}.
     - Reduce the test time duration to its half $\frac{T_{test}}{2}$.
     - Determine $\bar{R}_{\mathrm{eff\ OnR\ Rx}}\left(\frac{T_{test}}{2}\right)$.
     - The test time is long enough when

$$0{,}99 \leq \frac{\bar{R}_{\mathrm{eff\ OnR\ Rx}}(T_{test})}{\bar{R}_{\mathrm{eff\ OnR\ Rx}}\left(\frac{T_{test}}{2}\right)} \leq 1{,}01. \qquad \text{(I.3.1)}$$

   - To check whether the receive power level P_{Rx} at each and every antenna input of the DUT is chosen sufficiently high for ideal reception conditions, following steps can be performed:

     - Determine $\bar{R}_{eff\ OnR\ Rx}(P_{Rx})$ for the full receive power level P_{Rx}.
     - Reduce the receive power level by 6 dB to $P_{Rx} - 6\ dB$.
     - Determine $\bar{R}_{\mathrm{eff\ OnR\ Rx}}(P_{Rx} - 6\ dB)$.
     - The receive power level is high enough when

$$0{,}99 \leq \frac{\bar{R}_{\mathrm{eff\ OnR\ Rx}}(P_{Rx})}{\bar{R}_{\mathrm{eff\ OnR\ Rx}}(P_{Rx} - 6\ dB)} \leq 1{,}01 \qquad \text{(I.3.2)}$$

- If the test time duration T_{test} is chosen sufficiently long and the receive power level is sufficiently high, then the average transmitted effective data rate $\bar{R}_{eff\,OnR\,Tx}$ can be treated as equal to the measured $\bar{R}_{eff\,OnR\,Rx}$.

2) Set the signal power level at the DUT receiver input(s) 6 dB above the effective data-rate-dependent sensitivity limit specified in clause 5.3.

3) Set the CW frequency to f_1 according to clause 6.3.4.

4) Raise the power of the interfering signal until the measured average effective data rate $\bar{R}_{eff\,OnR\,Rx}$ reaches 90 % of $\bar{R}_{eff\,OnR\,Tx}$ as determined in step 1) under ideal conditions. I.e., the packet error rate reaches PER = 0,1. When adjusting the signal power level stepwise, the power level step where the packet error rate is just below 0,1 ($PER \leq 0,1$) should be used for the data rate measurement in the next step.

5) Determine the average transmitted effective data rate for a hypothetical continuous transmission $\bar{R}_{eff\,Tx} = \frac{\bar{R}_{eff\,OnR\,Tx}}{\bar{T}_{onR}}$ and calculate the ACR selectivity limit ACR_{req} from Equation (6.3.3) or the AACR selectivity limit $AACR_{req}$ from Equation (6.3.6), using this average effective data rate $\bar{R}_{eff\,Tx} = R_{eff}$ for PER = 0,1.

6) If the signal power level at the interferer outputs is above the selectivity limit, then the test is passed.

7) If the performance criteria as specified in Equation (6.3.3) or Equation (6.3.6) and as tested in step 6) is not met, steps 3) to 6) are repeated after that the frequency of the interferer signal set in step 3) has been set to f_2.

8) If the test did not pass for f_1 and f_2, then the test is considered to have failed.

History

Document history		
V1.1.1	May 2022	Publication