Multi-Channel Operation (MCO); Part 2; Technical capabilities and limits

CAR 2 CAR Communication Consortium

About the C2C-CC

Enhancing road safety and traffic efficiency by means of Cooperative Intelligent Transport Systems and Services (C-ITS) is the dedicated goal of the CAR 2 CAR Communication Consortium. The industrial driven, non-commercial association was founded in 2002 by vehicle manufacturers affiliated with the idea of cooperative road traffic based on Vehicle-to-Vehicle Communications (V2V) and supported by Vehicle-to-Infrastructure Communications (V2I). Today, the Consortium comprises 61 members, with 11 vehicle manufacturers, 31 equipment suppliers and 29 research organisations.

Over the years, the CAR 2 CAR Communication Consortium has evolved to be one of the key players in preparing the initial deployment of C-ITS in Europe and the subsequent innovation phases. CAR 2 CAR members focus on wireless V2V communication applications based on ITS-G5 and concentrate all efforts on creating standards to ensure the interoperability of cooperative systems, spanning all vehicle classes across borders and brands. As a key contributor, the CAR 2 CAR Communication Consortium works in close cooperation with the European and international standardisation organisations such as ETSI and CEN.

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Document information

Number:	**2084**	**Version:**	1.0.0	**Date:**	03/09/2020
Title:	**Multi-Channel Operation (MCO) Technical capabilities and limits**			**Document Type:**	White Paper
Release:	n.a.				
Release Status:	Public				
Status:	Final				

Changes since last version

Date	Changes	Edited by	Approved
03/09/2020	Initial setup of document	Release Management	Steering Committee

Table 1: Changes since last version

Title:	**Document Initial skeleton**
Explanatory notes:	**This paper focus on the 5.9 GHz Safety related Band usage, based on the existing usage via ITS-G5 of the Control channel with focus on European deployment of C-ITS Day-1 applications and extended use for additional safety and Road Transport Automation applications in other channels. It expects that other communications may be used as part of a Hybrid communication for additional information exchange and to realize redundancy due to functional safety and other none functional related requirements.** **This paper is part 2 of 3 with:** **1. Functional requirements** **2. Technology capabilities and limitations** **3. MCO concept** **For MCO, the Release 1 and 2 applications, services and use cases are considered and it is assumed that prioritization is based on existing Release 1 ITS-G5 initial deployed applications.**

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Definitions

Unicast	Unicast is the term used to describe communication where a piece of information is sent from one point to another point. Unicast transmission, in which a packet is sent from a single source to a specified destination, is still the predominant form of transmission on LANs and within the Internet. All LANs (e.g. Ethernet) and IP networks support the unicast transfer mode, and most users are familiar with the standard unicast applications (e.g. http, smtp, ftp and telnet) which employ the TCP transport protocol.
Existing	Something Exists when it is actively in use now.
Similar	Something is Similar when it behaves, acts and/or looks almost the same
C-ITS Methodology	Sharing transport (traffic situation) related information among Road stakeholders, openly and for free, such that each stakeholder can improve its awareness about actual traffic situations with the sole aim of improving traffic safety and traffic efficiency.

Abbreviations

ACL	Adjacent Channel Leakage
ACLR	Adjacent Channel Leakage Ratio
ACR	Adjacent Channel Rejection
ACS	Adjacent Channel Selectivity
CAM	Cooperative Awareness Message
CBTC	Communication Bases Train Control
C-ITS	Cooperative Intelligent Transportation Systems
CSMA/CA	Carrier Sense Multiple Access with Collision Avoidance
DC	Duty Cycle
DENM	Decentralized Environmental Notification Message
e.i.r.p.	Equivalent isotropic radiated power
ETSI	European Telecommunications Standards Institute
IEEE	Institute of Electrical and Electronic Engineering
ITS	Intelligent Transportation Systems
ITS-S	Intelligent Transportation Systems Station
MCO	Multi-Channel Operation
PSD	Power Spectral density
QAM	Quadrature Amplitude modulation
QPSK	Quadrature Phase sift keying
SNR	Signal to noise ratio
V2I	Vehicle to Infrastructure
V2V	Vehicle to Vehicle

1 Introduction

1.1 Abstract

Initial deployment of Cooperative Intelligent Transportation Systems (C-ITS) Safety related applications has been established by front runners starting in 2018 and extended at large scale end 2019 confirmed by the C-ITS Deployment Group [ER-2]. In the meantime, many new application initiatives have been taking shape requiring additional information exchange making use of safety related spectrum channels.
For Day-1 Applications information exchange could be handled for initial deployment in one channel but for the exchange of data for new applications additional channels will have to be used. This report provides an analysis of the technical capabilities and limitations of a C-ITS systems using IEEE based technologies in a multiband operation. The focus will be put onto the adjacent and second adjacent channel coexistence behaviour of synchronously operating communication systems in a limited geographical area. The investigations will be based on the actual version of the harmonized standard EN 302 571 [ER-3] and the ITS-G5 access layer specification EN 302 663[ER-8]. As a result of the report, a better understanding of the possible application mix on adjacent channels and second adjacent channels should be given.

2 General considerations and requirements

2.1 Introduction

In this clause the general requirements and consideration will be presented. This part will include an overview over the spectrum regulatory constrains in Europe covered in the ECC Decision (08)01[ER-6] including the corresponding EC decision 2008/671/EC [ER-10] and the ECC Recommendation (08)01[ER-7]. Furthermore, the relevant parameters of the standards covering the ITS-G5 access layer in IEEE802.11-2016[ER-4], ETSI EN 302 571 V2.1.1[ER-3] and the access layer specification in ETSI EN302 663 [ER-8] will be presented.

2.2 CEPT and EU C-ITS spectrum regulation framework

The legal basis of the operation of an ITS-G5 system in the spectrum band 5.855MHz to 5.905MHz is the ECC decision (08)01[ER-6] and the ECC recommendation (08)01[ER-7] including the EC decision 2008/671/EC [ER-10]. In these legal acts the frequency band between 5855MHz and 5905MHz has been allocated to intelligent transport systems (ITS). The overall spectrum of 50MHz split into 5 channels with 10MHz. The lower 2 channels from 5855MHz to 5875MHz are for traffic efficiency application whereas the band 5875MHz to 5905MHz is allocated to traffic safety applications. The lower 2 channels overlap with the Short-Range device (SRD) allocation in the band 5725MHz to 5875MHz.

In the updated regulation in 2020 an additional 20 MHz have been made available. The additional band is spit into a 10MHz band fully available for safety regulation (5905MHz to 5915MHz) and a shared band between safety related road ITS and rail ITS (Urban Rail) (5915MHz to 5925MHz) where rail ITS has a priority. In Figure 1 the spectrum mask is depicted for an ITS system with (black line and green line) and without mitigation techniques (black line) to protect tolling operations in the band 5795MHz to 5815MHz.

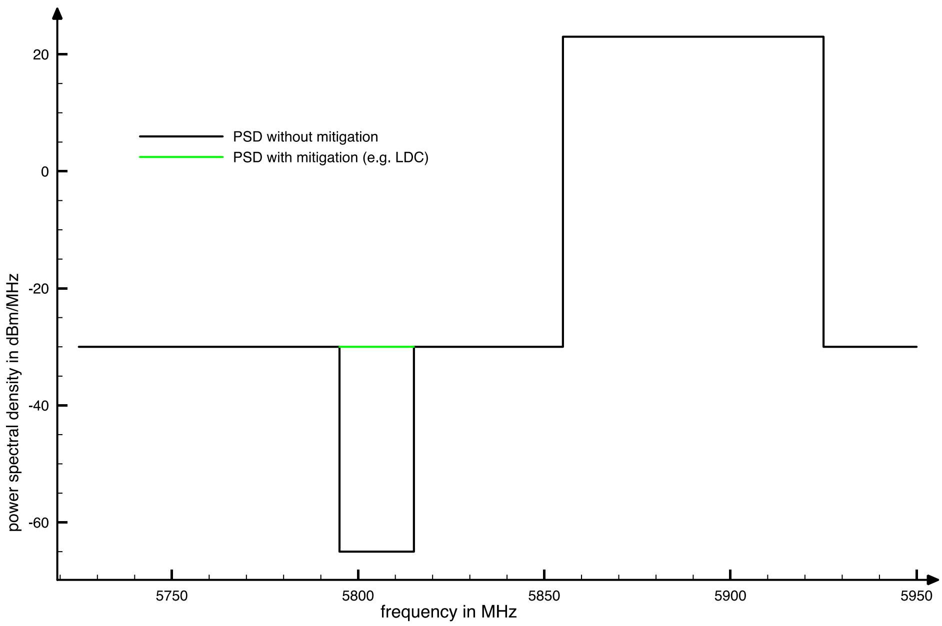

Figure 1: Regulatory spectrum mask in ECC Dec and Rec (08)01 in the year 2020 in dBm/MHz e.i.r.p.

The maximum allowed TX power density is 23dBm/MHz e.i.r.p. and maximum TX power of 33dBm e.r.i.p..

In the regulation the average duty cycle over 1 hour is limited to an average of 1% [ER-1] and a message length of 1ms with a peak limitation to 3% in 1 second. This allows for the transmission of typical messages like CAM on a regular pattern and some additional event driven emergency messages for a limited time (DENM).

In the European spectrum regulation specific considerations and rules have been included to mainly protect the proper operation of road tolling systems and Urban Rail system in the band 5915MHz to 5925MHz. The tolling system in the band 5795MHz to 5815MHz has to be protected by a significantly reduced spurious emission level of an ITS-G5 system in that band or equivalent mechanisms like the reduction of the duty cycle. The sharing mechanisms between Urban Rail systems in the band 5915MHz to 5925MHz are under development in ETSI. In this band the Urban Rail system has priority over any kind of road ITS system.

Since the band 5855MHz to 5875MHz is part of the Short Range Devices Regulation EC decision 2019/1345 [ER-12] specific spectrum polite rules need to be implemented allowing other SRDs to access the spectrum. For an ITS-G5 system these spectrum polite rules are inherently available by the CSMA/CA medium access protocol which uses a listen-before-talk mechanism with an energy threshold of -65dBm. In the shared spectrum in the band 5855MHz to 5975MHz this mechanism allows for the smooth operation of other system in this licensed exempt band.

In the band 5875MHz to 5925MHz ITS-G5 systems are operated on a co-primary allocation together with fixed satellite uplinks. These uplinks are operated at very limited number of positions in Europe. In the very close vicinity of these satellite base stations operating in the band 5875MHz to 5925MHz a range degradation of the ITS systems might occur. More detailed investigations (simulations, measurements) are needed in the future to evaluate the effect in real life situations.

2.3 IEEE802.11 based standards for ITS-G5

The access layer of ITS-G5 is based on the IEEE802.11-2016 [ER-4] access layer standard. This standard contains the 802.11p amendments for vehicular communication.
In this standard some characteristics of the TX and RX mask are specified. For the further investigation of multichannel operations in Europe the main relevant parameters are given in clause 2.4 of this white paper.

In 2019 IEEE802.11 has created a new working group to develop an enhanced version of the 802.11p access layer called 802.11bd[ER-5]. The main property of this new standard will be the full backwards compatibility with the existing 802.11p access layer including a smooth co-channel and adjacent channel interoperability.

Some feature of the new enhanced access layer for vehicular applications are:

- Enhanced channel coding based on LDPC code
- Multi-Antenna support for unicast
- Enhanced channel estimation capabilities using an increased number of pilot symbols
- Interoperable support of 20MHz channels including cross 10MHz channel sensing
    - This feature can be used for enhanced adjacent channel operation and interference mitigation.
- Support of repetition coding and DCM for higher range support when needed
- Higher order modulation with 256-QAM

- Increased number of tone (48 → 52)

In order to support multichannel operation, more enhanced TX characteristics are under discussion to be included. The parameters chosen in ETSI EN 302 663 V1.3.1 [ER-8] already take into account enhancements as compared to the original 802.11p[ER-4] standard.

802.11bd systems will support a mixed co-channel and adjacent channel traffic based on 11p and 11bd. Some features of 11bd might also be usable in existing 11p based ITS-G5 systems (e.g. repetition coding).

Up to now, no considerations have been added to look at MCO and required enhancements. Result of this study could be provided to the IEEE802.11bd group in order to take the MCO mode into account.

2.4 ETSI standards for C-ITS access layer

2.4.1 Overview

The main technical characteristics and operational principles of the ETSI ITS-G5 access layer are taken from the IEEE802.11p or better 802.11-2016[ER-4] specification. These characteristics are adapted to the European requirements (mainly spectrum requirements) in the ETSI EN 302 663[ER-8].

The MAC layer operation (mainly CSMA/CA access) and the related parameters are identical to the specification in IEEE802.11-2016[ER-4] and have not been changed in the ETSI EN302 663 access layer profile standard.

The main parameters which have been adapted are:

- Sensitivity
- TX mask or adjacent channel leakage ratio and
- Selectivity including blocking rejection

2.4.2 Sensitivity:

Table 2: Static receiver sensitivity[ER-8] [ER-4]

Transfer rate (Mbit/s)	Modulation	Coding rate	Minimum sensitivity for 10 MHz channel spacing (dBm) [ER-8]	Minimum sensitivity for 10 MHz channel spacing (dBm)
3	BPSK	1/2	-91	-85
4,5	BPSK	3/4	-90	-84
6	QPSK	1/2	-88	-82
9	QPSK	3/4	-86	-80
12	16-QAM	1/2	-83	-77
18	16-QAM	3/4	-79	-73
24	64-QAM	2/3	-75	-69
27	64-QAM	3/4	-74	-68

In table 2 the static receiver sensitivity of a ETIS-ITS-G5 receiver is depicted as specified in EN302 663 V1.3.1 [ER-8] and IEEE802.11-2016 [ER-4]. The dynamic sensitivity is 3dB below this static sensitivity. In EN 302 663 only a sensitivity value for the QPSK rate $R = ½$ is defined for the dynamic case in order to reduce the overall test effort. Real implementation will reach better values. In the context of this document we will use the values given in table 2 as reference values. The values in the IEEE802.11-2016 [ER-4] are less stringent by 6dB and no dynamic channel performance criterions are included.

2.4.3 Adjacent channel rejection:

Table 3: Limits for receiver adjacent channel rejection and alternate adjacent channel rejection[ER-8]

Transfer rate (Mbit/s)	Modulation	Coding rate	Adjacent channel rejection (dB)	Alternate adjacent channel rejection (dB)
3	BPSK	1/2	28	42
4,5	BPSK	3/4	27	41
6	QPSK	1/2	25	39
9	QPSK	3/4	23	37
12	16-QAM	1/2	20	34
18	16-QAM	3/4	16	30
24	64-QAM	2/3	12	26
27	64-QAM	3/4	11	25

In Table 3 the values for the adjacent channel rejection are given as defined in EN302 663 V1.3.1. These values correspond to the enhanced rejection values as define in IEEE802.11-2016.

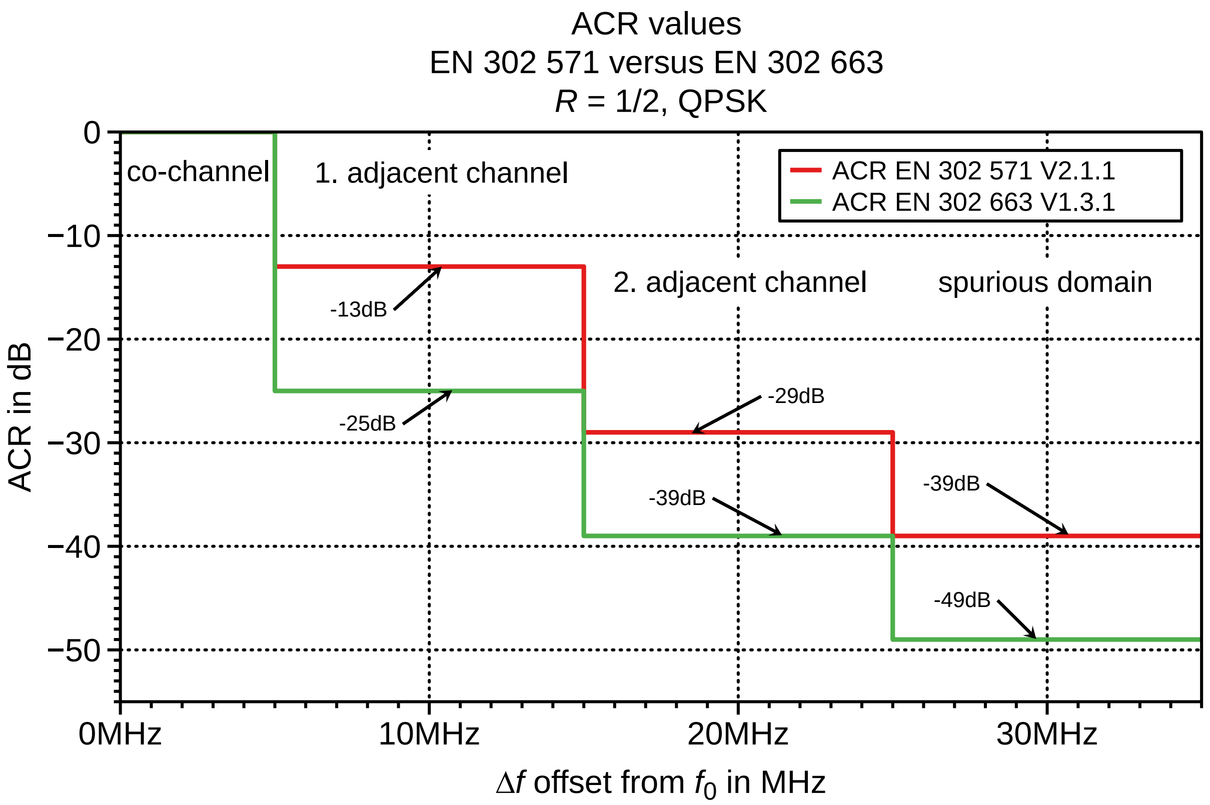

Figure 2: Adjacent channel rejection EN302 571 V2.1.1 [ER-3] and EN 302 663 V1.3.1, QPSK with R = ½ [ER-8]

In Figure 2 it can be seen that the enhanced selectivity figure in EN302 663V1.3.1 are significantly more stringent than the one originally specified in the harmonized standard EN302 571 V2.1.1.

The ACR is a modulation and coding scheme dependent parameter. For further investigations and the direct comparison with the adjacent channel leakage effect the adjacent channel selectivity (ACS) is a better value to be taken into account. From the ACR value given in the EN 302 663 the modulation and coding scheme independent ACS can be calculated as follows:

$$ACS = ACR + 3dB + SNR$$

Where SNR represents the required SNR value for a given modulation (for QPSK with R = ½ we assume 6dB). The 3dB are the margin taken in EN 302 663V1.3.1 for the ACR measurement procedure.

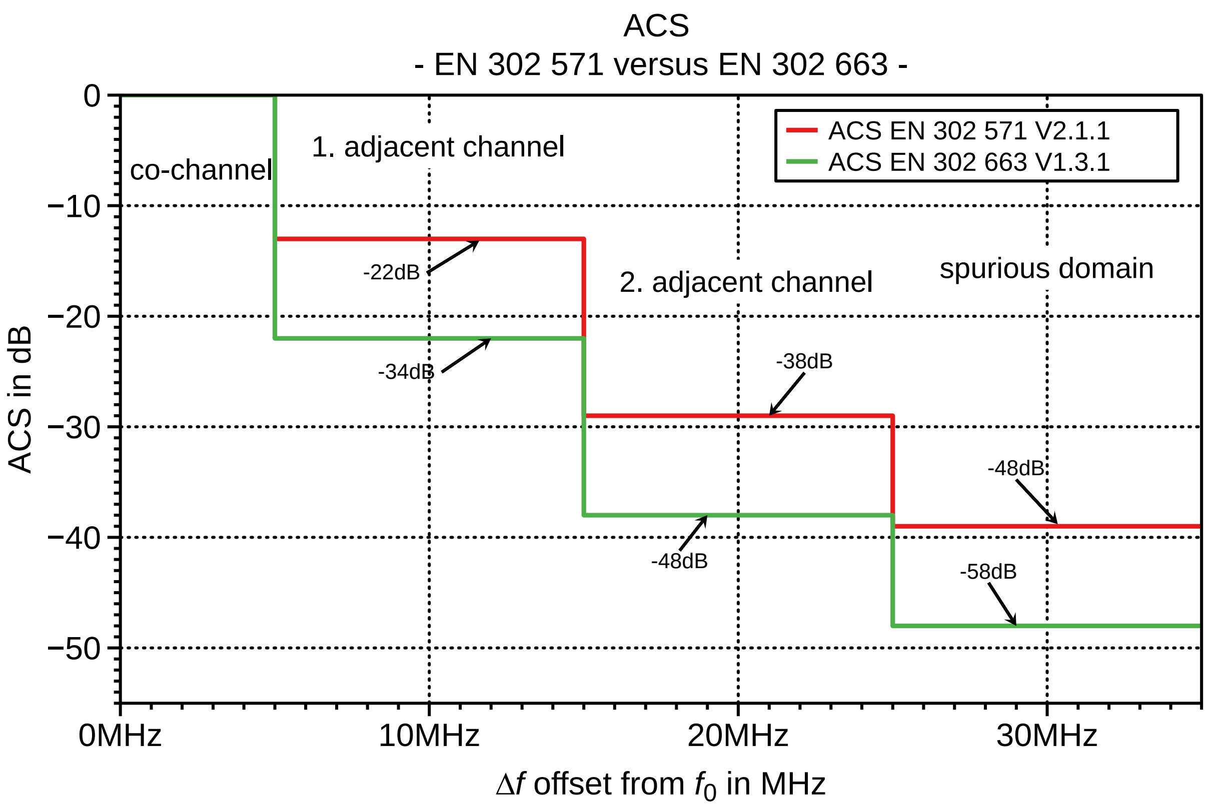

Figure 3: Adjacent channel selectivity ACS based on EN302 571 V2.1.1 [ER-3] and EN 302 663 V1.3.1, QPSK with R = ½ [ER-8]

In Figure 3 the resulting ACS values are depicted for EN 302 571 V2.1.1 and EN 302 663 V1.3.1. In Figure 3 the ACS value are depicted as attenuation value and thus they are negative.

The minimum ACS value for the first adjacent channel is -34dB. That means, for a 33dBm interfering transmitter in the adjacent channel the victim receiver will experience a worst-case interference level of -1dBm in 10MHz (plus path loss and other effects) from the selectivity effects of the RX. For a 23dBm TX level this value is -11dBm.
It has to be noted that the ACR values are defined for the complete 10MHz band and have to be reached at the band edges. In real systems, the ACR value will increase with the distance to the band edge. In order to have a more realistic selectivity performance the ACR value has to be interpolated between the specified frequency points (e.g. 10MHz to 20MHz) and then a linear integrated value for the ACR and ACS can be calculated. Taking this effect into account, the resulting values are better than the specified values. The resulting equivalent interference power levels are given in Figure 4. It can be seen that the values are almost 3dB better than the worst-case values (-3,8dB versus -1dB).

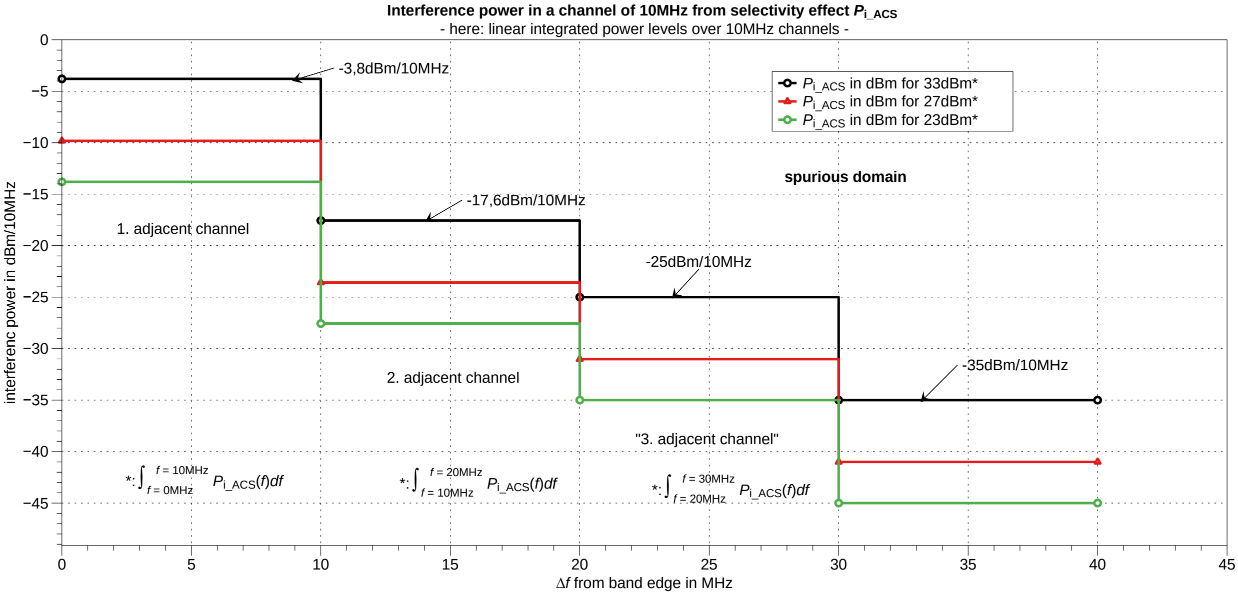

Figure 4: Adjacent channel selectivity ACS: Interference power levels using linear integration

2.4.4 TX spectrum mask:

In the draft ETSI EN 302 571 V2.1.9 [ER-13] from January 2020 the TX spectrum mask as depicted in Table 4 and Figure 5 is specified. This mask is the same mask as defined in EN 302 571V2.1.0 [ER-3]. It specifies a spectrum mask in absolute values and a measurement bandwidth of 100 kHz. All ITS-G5 devices independent of the transmit power have to fulfil this mask. In real operation it can be assumed that a device with less than the maximum allowed 33dBm e.i.r.p. TX power will have a reduced adjacent channel power level. Nevertheless, the reduction will not be fully proportional to the TX power reduction and it is not specified in the ENs.

Table 4: Out-of-band emission limits[ER-13]

Frequency offset to carrier frequency (MHz)	Emission limits (dBm e.i.r.p.)	Measurement bandwidth
± 5.0	-13	100 kHz
± 5.5	-19	100 kHz
± 10	-27	100 kHz
± 15	-37	100 kHz
± 25	-40	100 kHz

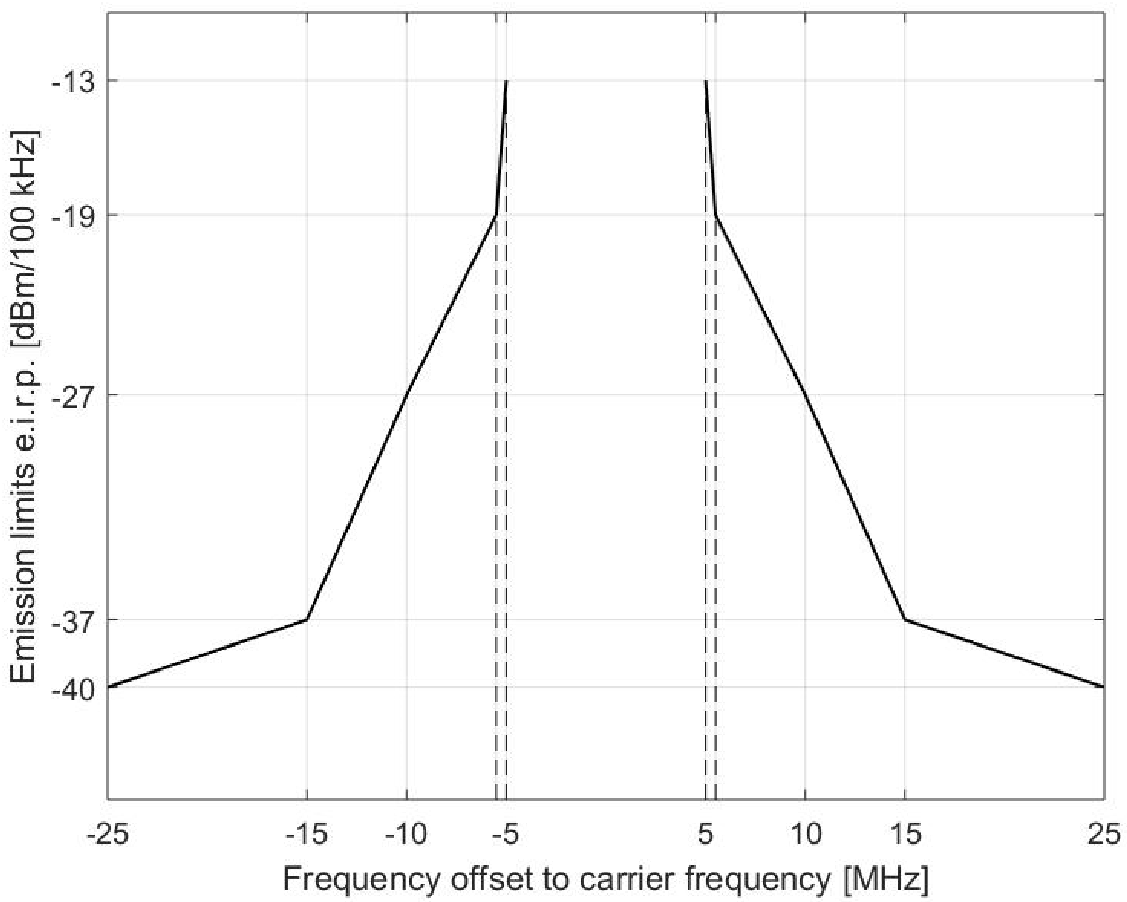

Figure 5: Transmitter spectrum mask EN 302 571 [ER-13]

Based on the figures in Table 4 the interfering power in the adjacent channel resulting from the adjacent channel leakage (ACL)/ out of band emission for a 33dBm interferer TX level will be around -2,5dBm in the 10MHz first adjacent channel and -18,2dBm in the second adjacent channel. These values are the integration over 10MHz channel bandwidth using the values in Table 4. For lower TX power the values will decrease.

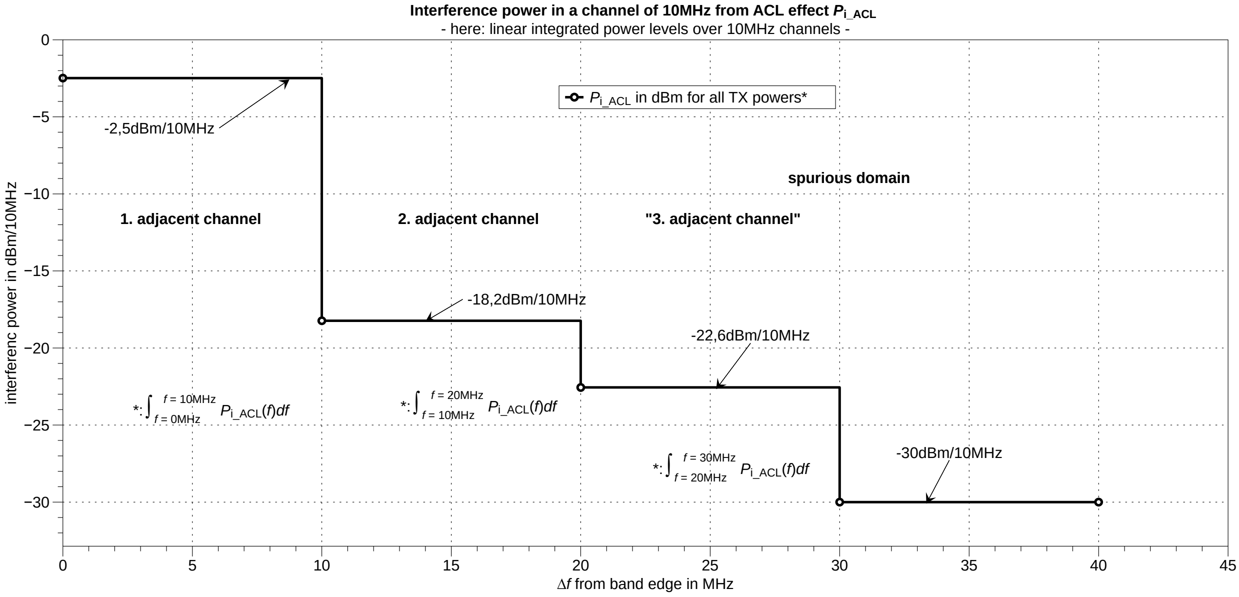

Figure 6: ACL P_{i_ACL} based on EN 302 571[ER-13]

2.5 Conclusion

Two parameters in the set off specifications will mainly govern the physical layer MCO behaviour of an ITS-G5 system:

- Selectivity (Adjacent channel selectivity)
- TX spectrum mask (Adjacent channel leakage or out off band emission)

If we consider the raw figure given in the specification it can be concluded that the main limiting factor for the MCO specification for a system using 33dBm TX power will be the ACL value taken from the TX mask of the system. In this case the interference created by the transmitter in the adjacent channel is 1,3dB higher than the effect resulting from the selectivity.
For lower TX powers this difference will even increase since the limits for the TX mask are given in absolute values whereas the selectivity limits are given in relative values relative to the interference level in the adjacent channel. Thus, a decreased TX power of the interferer in the adjacent channel will linearly decrease the interference effect from the selectivity effect, see Figure 7. In the worst-case the unwanted emission level of the same interfering transmitter will not decrease.
For the optimization of the physical layer MCO behaviour of an ITS-G5 system a more detailed specification of the TX power mask and thus the ACLR for the different power classes would be required.

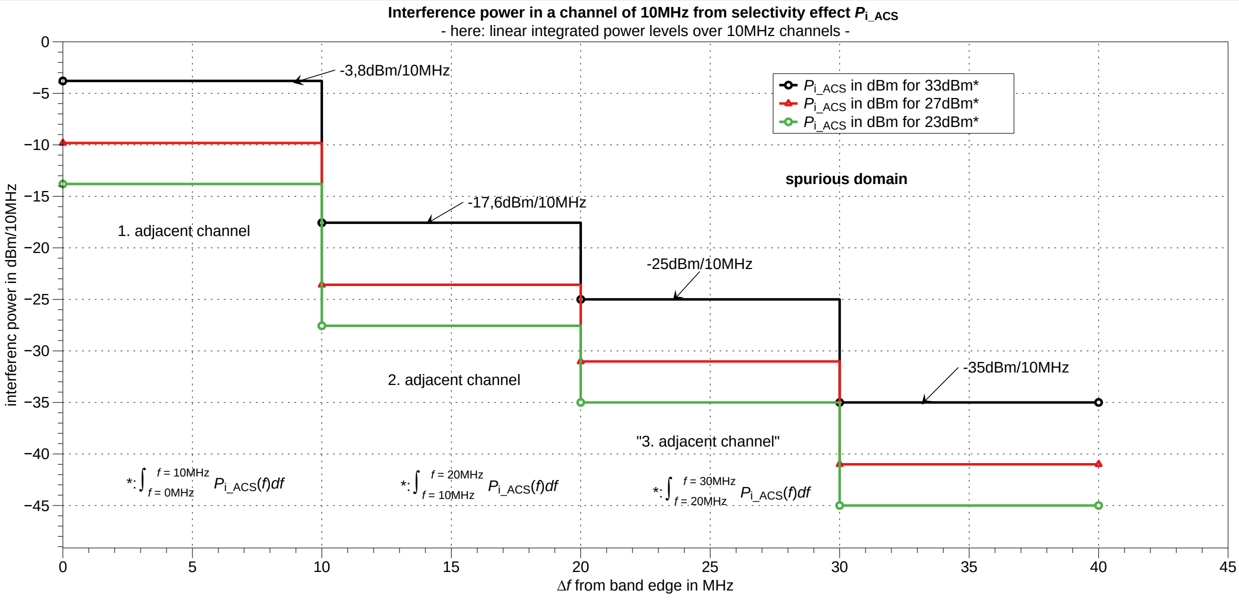

Figure 7: Effective interference levels P_{i_ACS} from ACS effect for different TX power levels of the interfering transmitter.

3 Multi-channel interference effects

3.1 Overview

In a multi-channel operation of a wireless systems different intra-system interference effect have to be considered. These effects can lead to a significant performance degradation of the system or even a complete failure of the system. In order to understand the possible mitigation techniques these effects will be present in this section. Both transmitter and receiver parameters have an impact on the performance in an MCO environment.

In Figure 8 the basic effect of the interfering effects in an MCO operation is depicted with the focus onto the direct adjacent channel. Similar effects can be observed for the second adjacent channel, spurious emissions and any kind of blocking signal further away from the wanted channel.

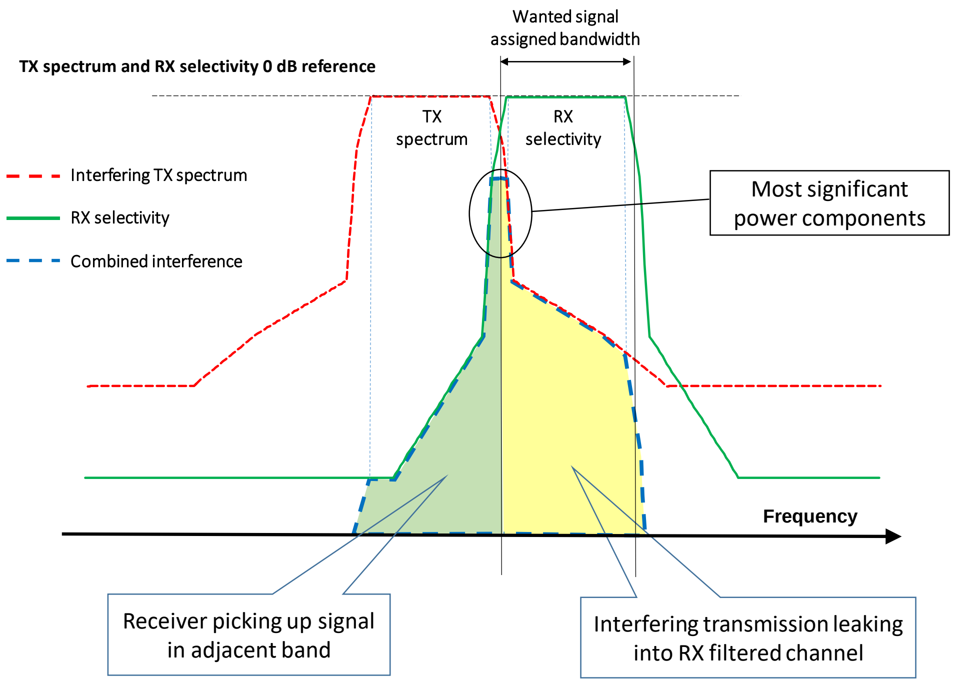

Figure 8: Impact of an interfering transmitter and a victim receiver on the reception of wanted signals, see ECC Report 310[ER-9]

Note: Here the out-of-band emissions in the wanted signal bandwidth is the main factor.

3.2 Unwanted emissions

3.2.1 Overview

Unwanted emissions are all kinds of emission of an interfering system which are not in the wanted emission band of this system. The unwanted emissions can be split into two main parts:

- Adjacent and second adjacent channel leakage or emissions and
- Spurious emissions

Unwanted emissions lead to interfering energy in the wanted band of the victim system. Unwanted emissions cannot be filtered by the victim system since the interfering energy of is in the wanted band of the victim system. Unwanted emissions can be reduced by e.g. signal design and transmitter filtering at the interfering transmitter.

3.2.2 Adjacent and second adjacent channel leakage

The effects of the adjacent and second adjacent channel leakage of a transmitter is described by the transmitter mask. For an ITS-G5 system this mask is defined in EN302 571 [ER-3]. From the victim receiver side this effect cannot be mitigated by any kind of filtering. The leaked energy of the interfering transmitter is part of the wanted signal to be received and leads to an increased noise level. In order to improve the behaviour here the TX mask has to be defined more stringent.

3.2.3 Spurious emissions

The spurious domain frequency band starts at 250% of the carrier bandwidth above and below the centre frequency of the emission of the interfering systems. For a 10MHz system this is the 3. Adjacent channel starting at 20MHz separation form the band edge of the reference channel. The levels of spurious emissions are regulated in ECC-Rec 74-01 [ER-11]. For the MCO considerations the levels of spurious emission (-30dBm/MHz e.i.r.p.) and the probability of occurrence are very low as compared to the adjacent channel effects. Typically, the real value of the interfering power in the spurious domain is significantly lower. Thus, they will not be considered further in this report.

3.3 Blocking and selectivity

Blocking refers to the reduction of the receiver sensitivity, thus the degradation of its performance, in the presence of an off-channel interfering signal; the frequency offset of the interfering signal should generally cover a relatively large range of frequencies around the wanted signal. The reduction of the sensitivity of the receiver is called “desensitisation” [ER-9]. For the 1st adjacent channel and the 2nd adjacent channel the capability of a receiver withstanding these kinds of interference are specified as adjacent channel rejection ACR (see clause 2.4 of this report) or adjacent channel selectivity ACS.
The robustness of the receiver against interfering signals further away than the 1st or 2nd adjacent channel are typically specified as blocking rejection.

3.4 Combined unwanted emission and selectivity effects

For the evaluation and simulation of the interfering effects in an MCO operation a combination of the two main effects (ACLR and ACS) into a single parameter will simplify the investigations. By combining and adding up the two interfering effects an interfering transmitter in an adjacent channel can be modelled as a simple interfering source transmitting a specific interference power. All relevant filtering effects can be included into a single figure $P_{\mathrm{TX\_int\_eff}}$, which is the transmitted effective interference power seen in a reference channel at the position of the interfering transmitter. $P_{\mathrm{TX\_int\_eff}}$ is dependent on the specified values for the TX power mask, the ACR or ACS, the transmit power of the interfering transmitter and the chosen adjacent channel. For the co-channel case, $P_{TX\_int\_eff}$ would be the actual TX power of the interfering transmitter.

$$P_{TX\_int\_eff} = P_{i\_ACL} + P_{i\_ACS}$$

The effective transmitted interference power of an interfering transmitter is depicted in Figure 9 for a 23dBm interfering transmitter.

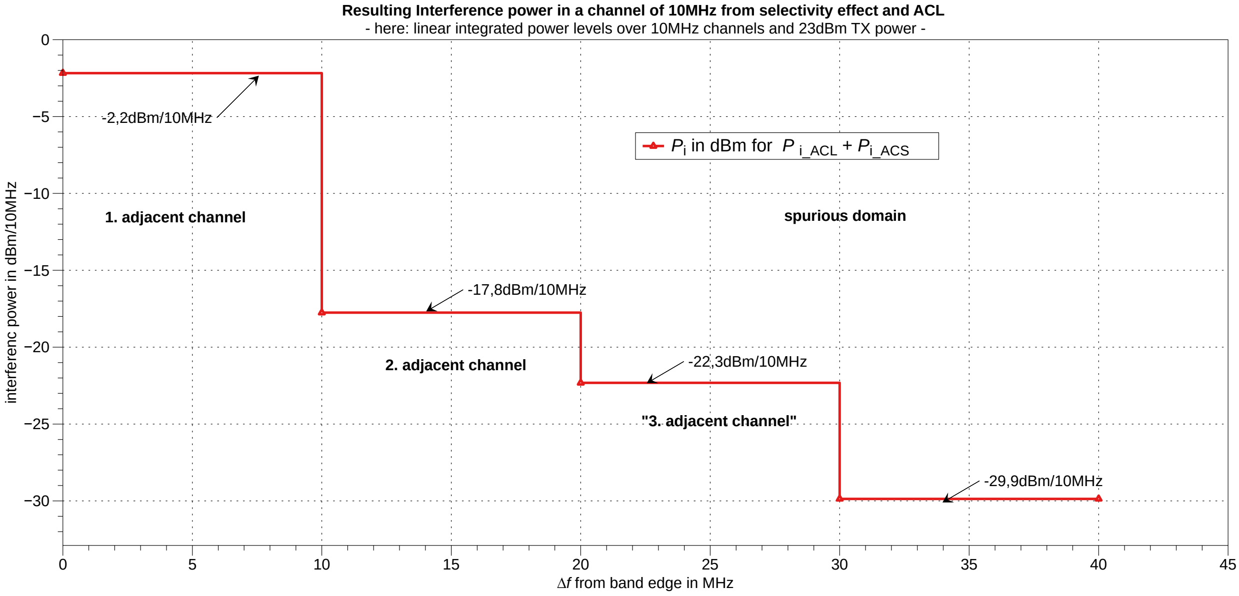

Figure 9: Effective interference power at the interfering TX $P_{TX\_int\_eff}$ as combination of ACLR and ACS effect

Based on $P_{TX\_int\_eff}$ the interfering power at the antenna of the victim receiver $P_{RX\_int\_eff}$ can be calculated by taking into account the actual pathloss PL between the interfering transmitter and the victim receiver.

$$P_{RX\_int\_eff}[\text{mW}] = PL * P_{TX\_int\_eff}[\text{mW}] \text{ or}$$

$$P_{RX\_int\_eff}[\text{dBm}] = P_{TX\_int\_eff}[\text{dBm}] - PL[\text{dB}]$$

3.5 Other effect

3.5.1 Overloading

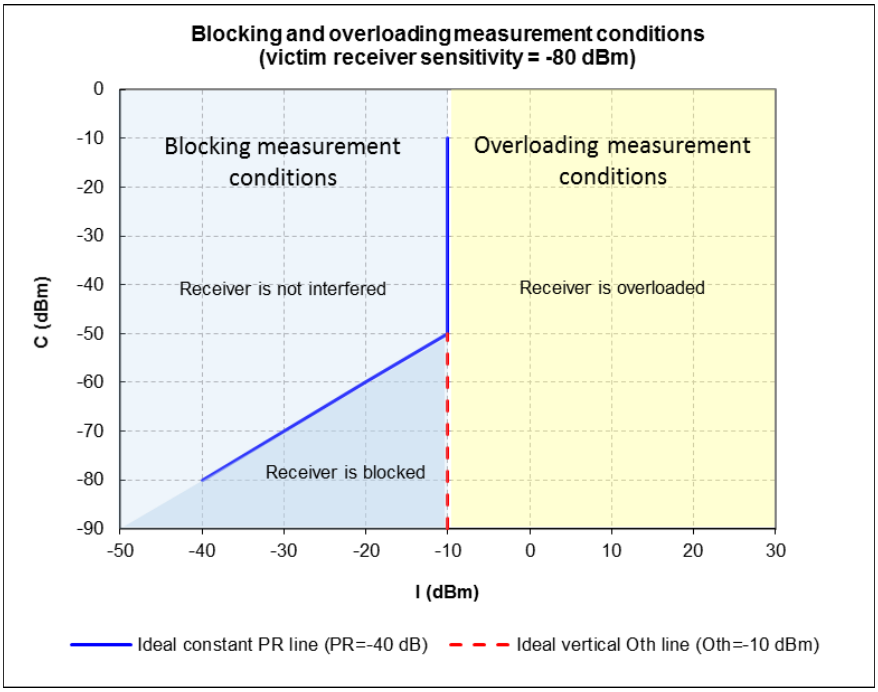

Figure 10: Receiver blocking and overloading measurement ranges[ER-9]

Blocking and overloading of a receiver are two different phenomena and should not be confused. Figure 10 shows the C(I) curve of an ideal receiver with a protection ratio (PR) of -40 dB and an overloading threshold (Oth) of -10 dBm.

Overloading occurs when the receiver front-end is fully overloaded by a strong off channel interfering signal. This results in the degradation of the PR of the receiver due to the “gain compression” and “noise increase” caused respectively by the third-order and second-order nonlinearity of the receiver LNA. The receiver selectivity also affects the overloading threshold level. In such case the interfering signal level expressed in dBm is called the «Overloading threshold» of the receiver.
When the receiver front-end is fully overloaded the receiver may become “blind” and thus unable to receive anything at all in contrast to the blocking and unwanted emission effects where only the communication range will be reduced. Additionally, beyond the overloading threshold the receiver is interfered by the interfering signal independent of the wanted signal level, as explained in Figure 10 [ER-9].

3.5.2 Intermodulation[ER-9]

The Intermodulation phenomenon arises from non-linearity of the amplifier in the receiving chain. The theoretical output signal of the amplifier can be described by a polynomial formula in the form:

$$y(t) = ax + bx^2 + cx^3 + \ldots \qquad (1)$$

where ax is the wanted output and bx^2, cx^3, etc. are unwanted intermodulation products due to the mixing of two or more interfering signals. Intermodulation is the only parameter requiring two or more interfering signals.
When considering only two signals of frequencies f_1 and f_2, the amplifier will generate:

$$cx^3 = c(A_1\cos(\omega_1 t) + A_2\cos(\omega_2 t))^3 = c\frac{3}{4}A_1{}^2 A_2\cos(2\omega_1 t - \omega_2 t) + c\frac{3}{4}A_2{}^2 A_1\cos(2\omega_2 t - \omega_1 t) + \ldots \quad (2)$$

This means that two signals of frequencies $2f_1 - f_2$ and $2f_2 - f_1$ appear in the receiver: these are the third order intermodulation products. 2nd order products (and higher order even number products) do not appear within the receiver's bandwidth and can be ignored. Higher order odd number products can also have an impact, but not as significant as 3rd order products.

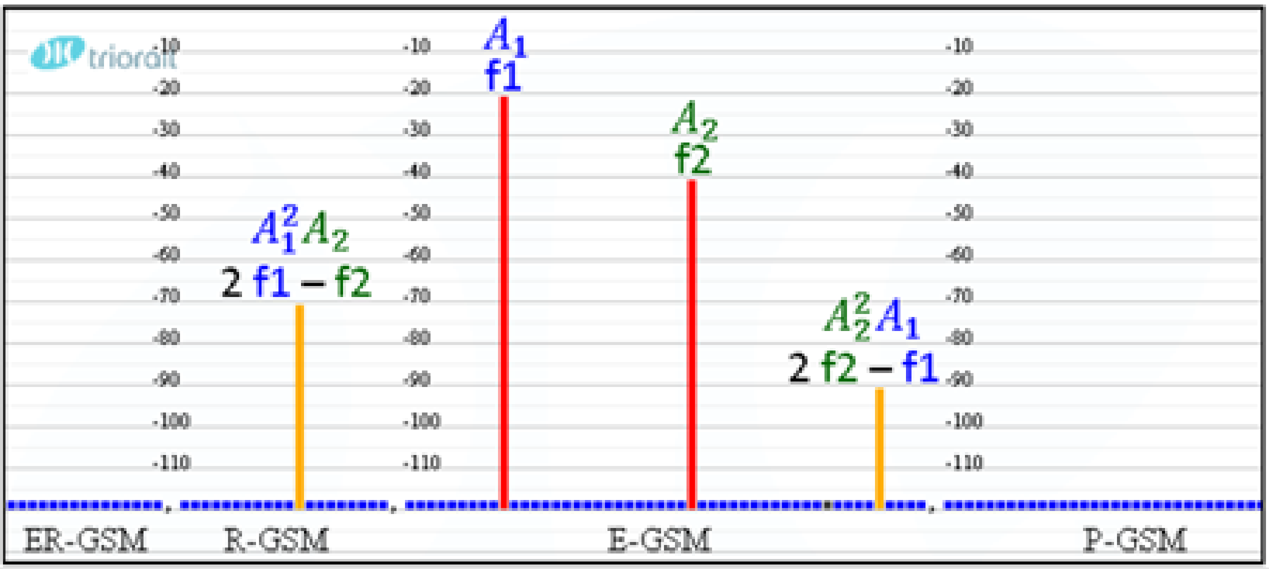

Figure 11: Generation of intermodulation products[ER-9]

A receiver operating at frequency f_0 is interfered by third order intermodulation products when the following conditions are met:

$$f_0 \approx 2f_1 - f_2 \text{ or } f_0 \approx 2f_2 - f_1$$

The strength of the signals A_1 and A_2 is above a given threshold. Note that some standards/specifications define one of the interfering signals (typically the signal close to the receiver) with a system specific modulation whereas the second one remains unmodulated.

3.5.3 CSMA/CA energy detection threshold

In cases where the potential interfering system in the adjacent channel operates with a very small distance from the victim receiver antenna, the generated interference by the interfering system can reach the level of the energy detection threshold of the CSMA/CA system. From the victim point of view this would lead to a positive sensing results and the transmission operation will be delayed. Here the adjacent channel interference will have a direct influence onto the transmission operation of the victim system. Furthermore, it could lead to an increased estimated channel load and thus a triggering of the DCC mechanism.

Based on a LoS transmission condition between the interfering TX with TX power of P_{TX_I} = 23dBm in the adjacent channel and the victim systems antenna with 8dBi antenna gain the this effect ca happen in a distance up to around 15m having in mind the energy detection threshold of -65dBm in a 10MHz channel. For the enhance TX spectrum mask investigate in section 4.3 of this report this range would be reduced to around 5 m.
Under very dense traffic conditions this effect might have to be taken into account especially when operating in DCC conditions.

3.6 Summary

In the scope of the definition of MCO the main effects to be taken into account are the adjacent channel leakage of the transmitter and the adjacent channel selectivity of the receiver. In addition, the energy detection threshold in the CSMA/CA process in the receiver have to be considered.
Other effects (e.g. overloading and intermodulation) of adjacent channel interference from any kind of device operation in the adjacent channels can influence the performance of the system. These effects are mainly related to very close proximity operation of the devices and thus need to be taken into account in the development process of the integrated device or of the multi-channel chips. These effects are very much related to the detailed architecture of the devices.
For further investigations in the scope of this report the focus will be put onto the ACL, ACS and energy detection threshold effects.

4 Performance evaluation

4.1 Introduction

In order to better understand the behaviour and restrictions of ITS in MCO mode a detailed analysis of the interference effects from the adjacent channels into a victim link are required. These effects will define the physical layer restrictions to be considered in the higher layer definition of MCO.
It will also give an insight into possible optimization and mitigation techniques which can be used to increase the efficiency of the MCO.

4.2 Channel models

In order to simplify the investigations a three slop pathloss model has been used in the following investigations.

The model proposed in ECC Report 68 [ER-14] is a three-slop propagation model with the following characteristics:

$$L_{FS} = \begin{cases} 20Log\left(\frac{\lambda}{4\pi d}\right) & d \le d_0 \\ 20Log\left(\frac{\lambda}{4\pi d_0}\right) - 10 n_0 Log\left(\frac{d}{d_0}\right) & d_0 < d \le d_1 \\ 20Log\left(\frac{\lambda}{4\pi d_0}\right) - 10 n_0 Log\left(\frac{d_1}{d_0}\right) - 10 n_1 Log\left(\frac{d}{d_1}\right) & \text{if } d > d_1 \end{cases} \quad (1)$$

The model parameters for the slop break points have been adapted to the specific characteristics of the ITS communication.

Table 5: Parameters for the propagation model used in this report

	MCO_Urban	MCO_Suburban	MCO_Rural
Breakpoint distance d_0 (m)	32	64	128
Pathloss factor n_0 beyond the first break point	3.8	3.3	2.8
Breakpoint distance d_1 (m)	64	128	512
Pathloss factor n_1 beyond the second breakpoint	4.3	3.8	3.3

As compared to the originally proposed models in ECC Report 68 [ER-14] the break point distances have been halved. These models are used for the wanted victim link and for the interfering link (the link between the interfering TX and the victim receiver). The model can easily be adapted to the actual requirements and scenarios to be investigated.

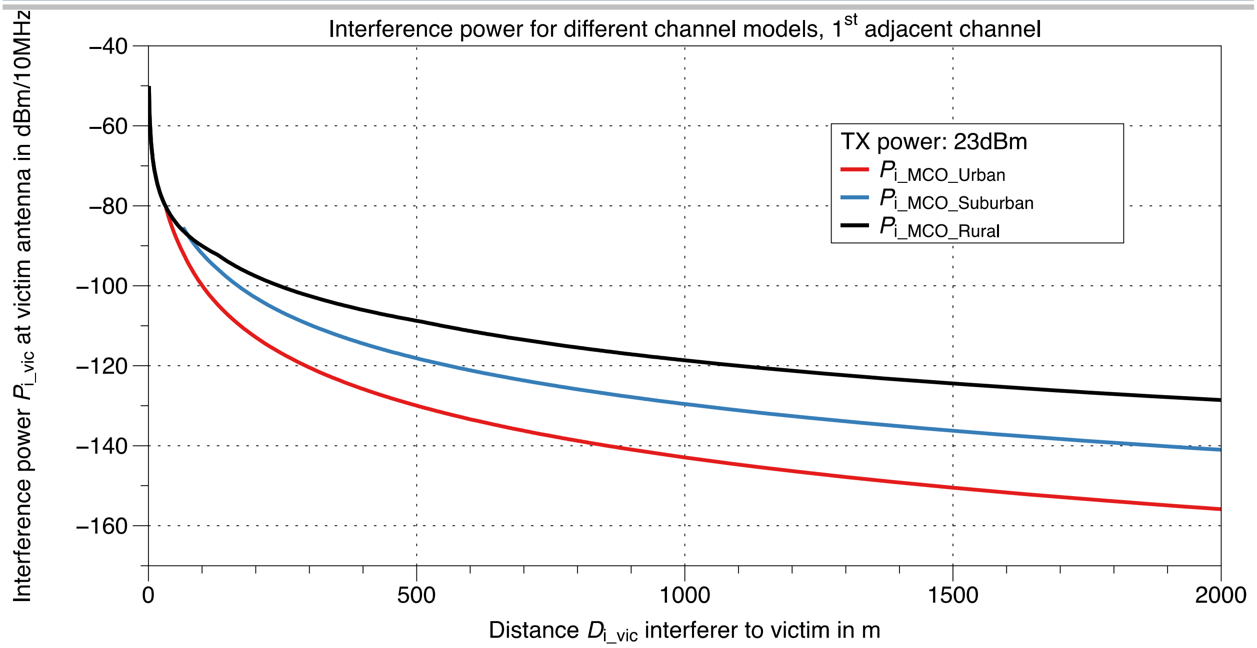

Figure 12: Combined interference power P_{i_vic} from 1st adjacent channel at victim antenna for the three channel models

In Figure 12 the combined interference power at the victim antenna P_{i_vic} generated by a interferer in the 1st adjacent channel with a TX power of 23dBm in distance D_{i_vic} for the three proposed static channel models is depicted.

4.3 Static interference evaluation

In order to better understand the effect of any kind of adjacent channel interference into a reference victim link the reduction of possible reception range of the victim link will be the initial parameter to be investigated. The static evaluation of the range reduction will present the worst-case effect of adjacent channel interference since here a 100% duty cycle of the interferer and the victim link is assumed. In reality the actual duty cycle of the interferer, the number of interferer and their distribution and the actual signal to be received by the victim receiver will significantly influence the overall performance reduction. These effects can only be evaluated in statistical simulations. In this section, only the range reduction by the adjacent channel interference for a 23dBm system will be depicted.

In Figure 13 the received power of the wanted link at the victim antenna connector for 23dBm TX power with a QPSK modulation and a coding rate R = ½ for different channel models is depicted. As an orientation the specified static sensitivity values given in EN 302 663 V1.3.1 are included in the figure without antenna gain (-88dBm) and with antenna gain of 8dBi.

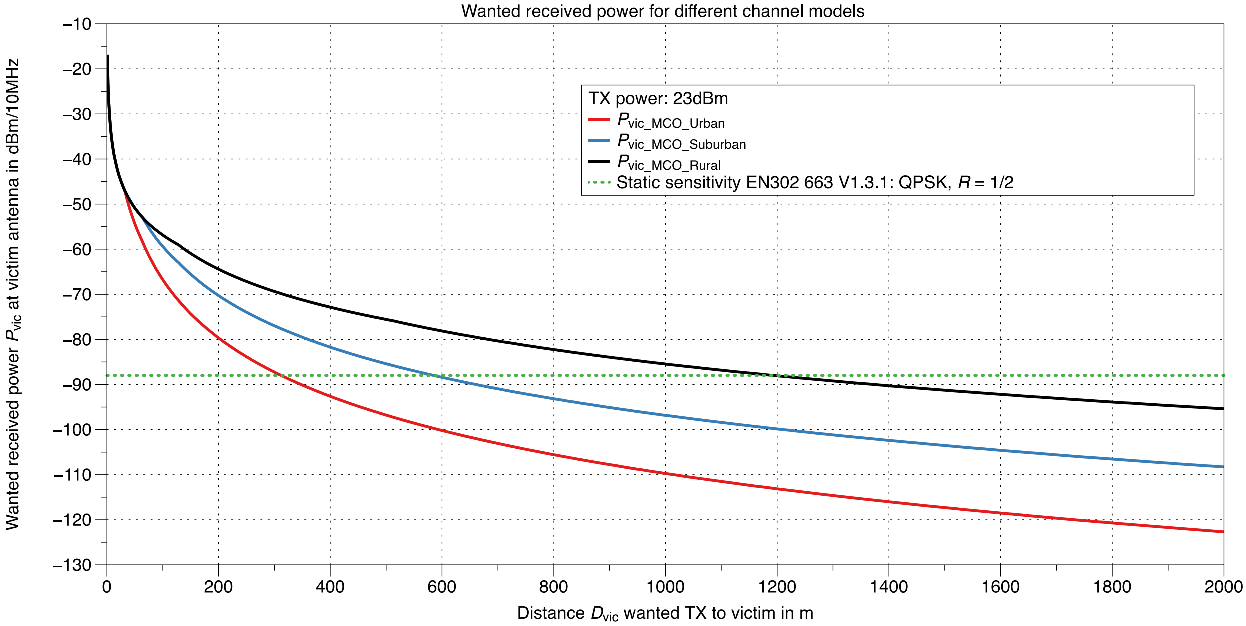

Figure 13: Wanted link: Received power at victim antenna connector for different distances to wanted TX and different channel models including 8dBi antenna gain

Under static conditions, the following ranges can be extracted from Figure 13:

- Urban environment with 23dBm TX power: 312m
- Suburban environment with 23dBm TX power: 585m
- Rural environment with 23dBm TX power: 1200m

In the following investigations these values are used as the reference values to compare with. Real systems operating in real environments will result in different range values.

In Figure 14 the range reduction due to an interferer in the 1st adjacent channel with a TX power of 23dBm is depicted for the three proposed channel models in urban, suburban and rural environments. In the urban environment it can be seen that an interferer in a distance of 120m and more will not influence the behaviour of the wanted receiver anymore. For the suburban environment this mitigation distance is in the order of 300m and 600m for the rural environment, see Figure 15.

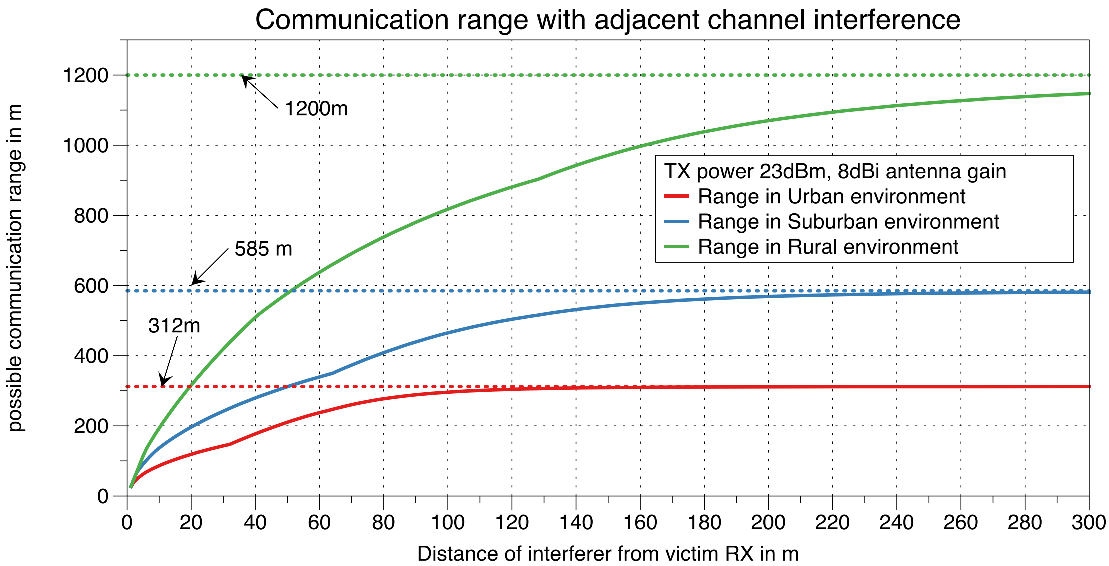

Figure 14: Range reduction due to 1st adjacent channel interference for 23dBm TX power

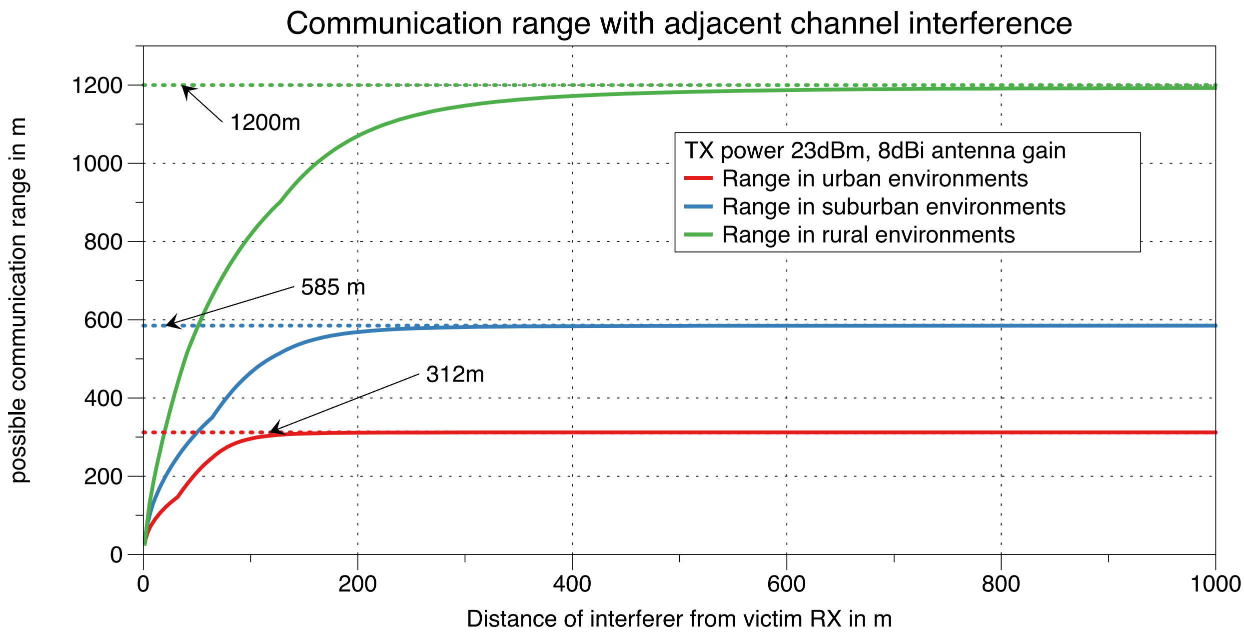

Figure 15: Range reduction due to 1st adjacent channel interference for 23dBm TX power, extended range figure

In Figure 16 and Figure 17 the interference effect from the 1st and 2nd adjacent channel interferences are depicted. It can be seen that the effective interreference range for a device operating in the 2nd adjacent channel is significantly lower as compared to the 1st adjacent channel operation. In an urban environment the effective interference range is up to around 50m, in a suburban environment 100m and in a rural environment 200m.

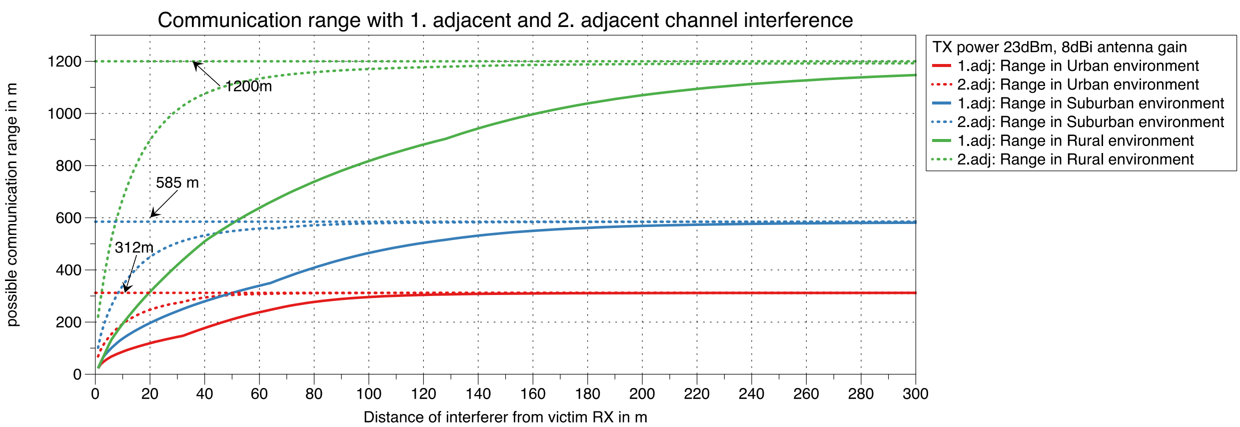

Figure 16: Range reduction due to 1st and 2nd adjacent channel interference for 23dBm TX power

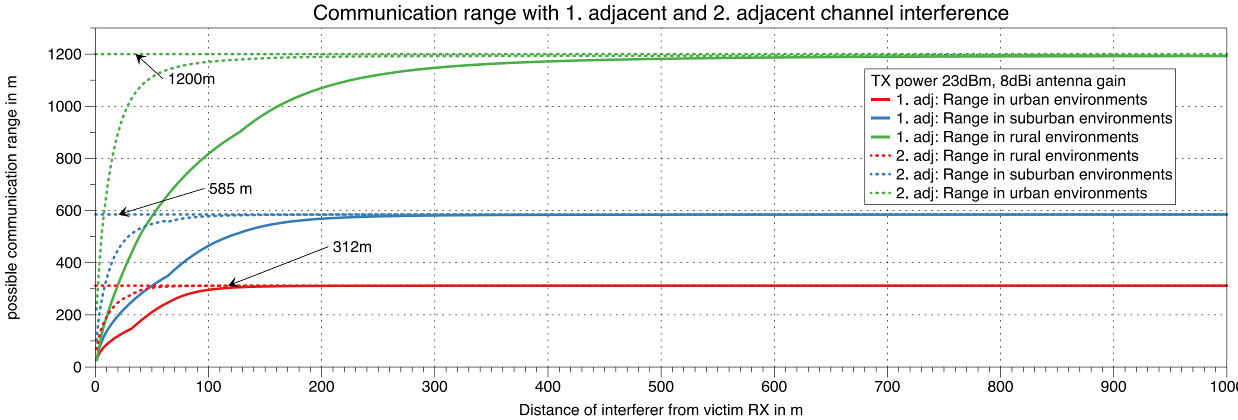

Figure 17: Range reduction due to 1st adjacent and 2nd channel interference for 23dBm TX power, extended range figure

In a further simulation an enhanced TX mask of the interfering transmitter has been assumed. In the following the TX mask is assumed to lead to the same level of interference as the interference effect from the selectivity effects. This would lead to a fully balanced specification of the two effects.

The resulting interference power levels $P_{i\_ACL\_enh}$ from the adjacent channel leakage effect are given in Figure 18.

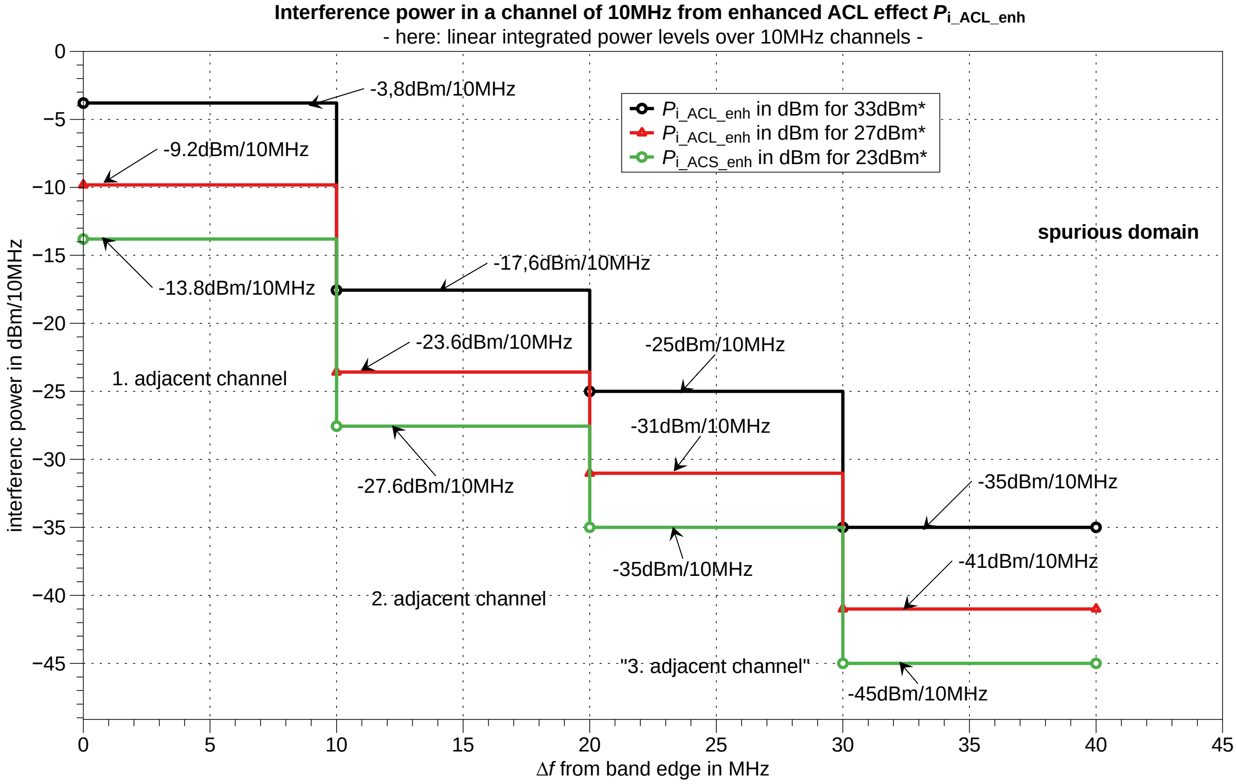

Figure 18: optimized adjacent channel leakage interference power $P_{i\_ACL\_enh}$ based on the ACS interference levels

The effective combined adjacent interference power from ACL and ACS are thus 3dB higher than the ACL value alone.

For a 23dBm interfering transmitter this would lead to:

- 1st adjacent channel: -10.8dBm/10MHz

- 2nd adjacent channel: -24.6dBm/10MHz
- 3rd adjacent channel: -32dBm/10MHz
- Further channels: -42dBm/10MHz

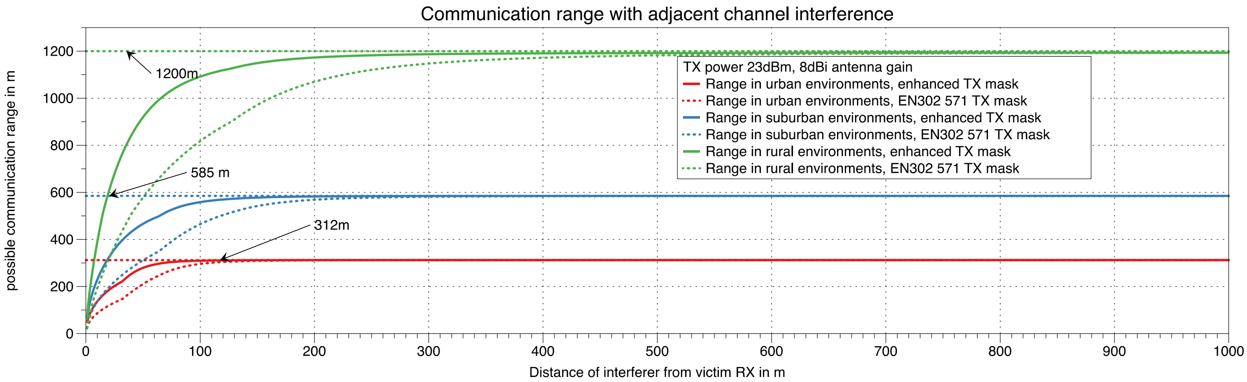

Figure 19: Range Comparison of EN302 571 TX mask with optimized adjacent channel leakage interference mask

In Figure 19 a range comparison between the TX mask in EN 302 571 and the enhanced mask is depicted. It can be seen that the interference range is significantly reduced and thus the risk of interference is optimized.

4.4 Statistical considerations simulations

The results presented in section 4.3 of this report are based on the calculation of the interference effects for a static case. The results present the interference effect in case a reception of a message transmitted at a given distance from the victim receiver collides fully with a message transmitted in an adjacent channel by an interfering transmitter.

In reality ITS operates with very low duty cycle and low message length. The interference case where a weak received packet will collide with a higher power interfering packet from the adjacent channel has low probability. These effects can only be investigated with more detailed simulation taking into account:

- the statistical behaviour of the wanted messages,
- the statistical behaviour of the interfering messages,
- the relevance area of the wanted communication and
- the corresponding interfering area.

The calculation in section 4.3 shows that in urban environments and an assumed minimum distance between the victim and interfering device in the adjacent channel only messages from station further away than around 40m are disturbed. The most relevant awareness messages in the close vicinity of the devices are not significantly disturbed.

More detailed simulations will be performed in the scope of the ETSI STF585.

4.5 Summary

In this section the most important adjacent channel interference effect for a multichannel operation have been investigated. In a first step a combined interference value has been derived combining the interference effects from the out-of-band emissions interfering system and the selectivity effects from the wanted system. Based on the proposed channel models the communication range reduction of the wanted link for different interferer distances has been calculated and depicted.

The following observation can be made:

- The specified selectivity in EN 302 663 V1.3.1 is significantly better than the value defined in the actual version of EN 302 571 V2.1.1.
- The corresponding TX mask (ACL) is defined as absolute value and can be seen as the main interfering factor.
- The interference ranges vary between 120m, 300m and 600m for the 1st adjacent channel and the a 23dBm TX system
- The interference ranges vary between 50m, 100m and 200m for the 2nd adjacent channel and the a 23dBm TX system
- The interference will not break the communication but just reduce the effective communication range of victim system, meaning that it will not be able to receive messages from devices further away than the possible communication distance.
- For typical worst-case interferer distances of 2 m, the wanted communication with neighbouring devices in the range of up to around 40 m will not be significantly disturbed.
- An enhanced TX mask with a balanced out-of-band emission limit equal to the selectivity effect will lead to a significantly further reduced interference range and thus interference risk.
- Any Physical layer optimization should focus first onto an optimization of the TX mask. In a first step the TX mask should be defined a relative mask in relation to the TX power.
- Statistical effect will further reduce the adjacent channel interference effects due to a low collision risk between messages.

5 Summary and recommendation

5.1 Introduction

In this report the limits of a multi-channel operation from the physical layer perspective has been investigated. In the further part of this section some proposals will be given. In this report the focus was the static interference scenarios. More detailed dynamic interference cases will be simulated in the scope of the ETSI STF585.
Nevertheless, this report can already give some advices for the future development of an MCO in ITS-G5 and optimization which should get priority in the development.
The calculated limits can be used a guidance for the definition of the channel split for a proper multi-channel operation ITS-G5.

5.2 Possible mitigation effects

The existing set of specifications (EN 302 571 and EN 302 663) define the TX spectrum mask and the selectivity requirements of ITS devices. The static interference investigation performed in the scope of this report have shown an imbalance between the TX mask (ACL) and the selectivity performance requirements. An improved MCO behaviour can be reached by an improved TX spectrum mask requirement. In a first step the spectrum mask should be defined separately for different power classes. This would already decrease the balance gap between the ACL and ACS values especially for lower TX power classes.
This recommendation should be taken into account in the definition of the future enhanced physical layer under development in IEEE802.11bd[ER-5]. Here the effect of the increase number of used carriers onto the spectrum mask and the selectivity has to be investigated in order to avoid any MCO performance degradation as compared to the existing physical layer based on IEEE802.11-2016[ER-4].

Any kind of selectivity improvement will only make sense after the TX mask improvements.

In IEEE 802.11bd an channel bonding option with 20MHz channel bandwidth is under discussion. Taking into account the results in this report and the possible improvement of the TX mask the no direct gain of this 20MHz option for MCO can be seen having in mind the reduced flexibility of this option.

For longer range messages and application with large relevance areas it has to be avoided that a number of consecutive messages from the same source are being disturbed. Here it is important to avoid any kind of non-managed time synchronization between the wanted system and the interfering system in the adjacent channels. This should be taken into account in the generation rules of the different messages.

In infrastructure installation the adjacent channel interference effective range can significantly be reduced by optimized antenna patterns with well-defined coverage areas. On the other hand, the antenna positioning at a height of up to 5m might lead to an increased portability to interfere with the vehicular antennas.

More enhanced coordination techniques based on the position of ITS stations could be envisaged if MCO application limitation require.

6 Annex A – References

[ER-1] CEPT ECC, ECC Decision (08)01: "The harmonised use of the 5875-5925 MHz frequency band for Intelligent Transport Systems (ITS)", approved 14 March 2008, Amended 6 March 2020: https://www.ecodocdb.dk/download/b470d271-048b/ECCDEC0801.PDF

[ER-2] C-ITS Deployment Group: http://c-its-deployment-group.eu

[ER-3] ETSI HEN 302 571 V2.1.0: 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

[ER-4] IEEE 802.11-2016 (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

[ER-5] IEEE 802.11bd: http://www.ieee802.org/11/Reports/tgbd_update.htm

[ER-6] ECC DEC (08)01: ECC Decision "The harmonised use of the 5875-5925 MHz frequency band for Intelligent Transport Systems (ITS)", https://www.ecodocdb.dk/download/b470d271-048b/ECCDEC0801.PDF

[ER-7] ECC REC (08)01: ECC Recommendation "Use of the band 5855-5875 MHz for Intelligent Transport Systems (ITS)", https://www.ecodocdb.dk/download/798c1836-20c6/REC0801.pdf

[ER-8] 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

[ER-9] ECC Report 310: "Evaluation of receiver parameters and the future role of receiver characteristics in spectrum management, including in sharing and compatibility studies", 2020.

[ER-10] EC decision 2008/671/EC: "Commission Decision of 5 August 2008 on the harmonised use of radio spectrum in the 5875-5905 MHz frequency band for safety related applications of Intelligent Transport Systems (ITS)", 2008

[ER-11] ECC REC 74-01: Unwanted emissions in the spurious domain, 29. May 2019,

[ER-12] EC Implementation Decision 2019/1345: " COMMISSION IMPLEMENTING DECISION (EU) 2019/1345 of 2 August 2019 amending Decision 2006/771/EC updating harmonised technical conditions in the area of radio spectrum use for short-range devices"

[ER-13] Draft ETSI EN302 571 V2.2.1: ETSI HEN 302 571 V2.1.9: "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", January 2020.

[ER-14] ECC Report 68:

■ End of Document ■