ETSI TR 102 960 V1.1.1 (2012-11)

Technical Report

Intelligent Transport Systems (ITS);
Mitigation techniques to avoid interference between European CEN Dedicated Short Range Communication (RTTT DSRC) equipment and Intelligent Transport Systems (ITS) operating in the 5 GHz frequency range;
Evaluation of mitigation methods and techniques

Reference

DTR/ITS-0040029

Keywords

DSRC, ITS, radio, RTTT

ETSI

650 Route des Lucioles
F-06921 Sophia Antipolis Cedex - FRANCE

Tel.: +33 4 92 94 42 00 Fax: +33 4 93 65 47 16

Siret N° 348 623 562 00017 - NAF 742 C
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Contents

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Foreword

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

Introduction

Without the use of special mitigation techniques, European CEN Dedicated Short Range Communication (DSRC) equipment operating in the frequency range from 5 795 MHz to 5 815 MHz might suffer from harmful interference caused by Intelligent Transport Systems (ITS) using adjacent frequency bands. The present document will evaluate the detailed need of mitigation techniques and the corresponding parameters to avoid this interference. The evaluation is based on simulations and measurements.

1 Scope

The present document presents the results of the evaluation of the potential coexistence issues between ITS-G5 and CEN DSRC tolling systems. The evaluation tests take into account a broad range of DSRC OBUs from different manufacturers. The evaluation consists of the definition of the evaluation scenarios, simulation results and results of evaluation measurements.

The present document is indented to guide the further work on coexistence mechanisms in ITS-G5 in order to guarantee a smooth coexistence between ITS-G5 and CEN DSRC systems.

2 References

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

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2.1 Normative references

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

Not applicable.

2.2 Informative references

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

[i.1] CEN EN 12795: "Road transport and traffic telematics - Dedicated Short Range, Communication (DSRC) - DSRC data link layer: medium access and logical link control".

[i.2] CEN EN 13372: "Road transport and traffic telematics - Dedicated Short Range Communication (DSRC) - Profiles for RTTT applications".

[i.3] CEN EN 12253: "Road transport and traffic telematics - Dedicated Short Range Communication (DSRC) - Physical layer using microwave at 5,8 GHz".

[i.4] ETSI TR 102 654: "Electromagnetic compatibility and Radio spectrum Matters (ERM); Road Transport and Traffic Telematics (RTTT); Co-location and Co-existence Considerations regarding Dedicated Short Range Communication (DSRC) transmission equipment and Intelligent Transport Systems (ITS) operating in the 5 GHz frequency range and other potential sources of interference".

[i.5] ETSI ES 202 663: "Intelligent Transport Systems (ITS); European profile standard for the physical and medium access control layer of Intelligent Transport systems operating in the 5 GHz frequency band".

[i.6] CEN EN 15509: "Road transport and traffic telematics - Electronic fee collection; Interoperability application profile DSRC".

[i.7] ETSI TS 102 792: "Intelligent Transport Systems (ITS); Mitigation techniques to avoid interference between European CEN Dedicated Short Range Communication (CEN DSRC) equipment and Intelligent Transport Systems (ITS) operating in the 5 GHz frequency range".

[i.8] ETSI TS 102 687: "Intelligent Transport Systems (ITS); Decentralized Congestion Control Mechanisms for Intelligent Transport Systems operating in the 5 GHz range; Access layer part".

[i.9] D.COMM.x.x, CVIS project deliverable: "CVIS COMM Interference measurements test report", February 2010.

[i.10] IEEE 802.11-2012: "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".

3 Definitions, symbols and abbreviations

3.1 Definitions

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

Mode A: Typical case with a typical path loss attenuation between RSU and OBU and e.g. 6 dB above sensitivity limit

Mode B: Worst case with a path attenuation leading to an operation of the OBU at the sensitivity limit

3.2 Symbols

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

P_{ITS}	ITS Transmit power level
PL	Path loss
PL_0	Reference Path Loss
P_{RX}	Received Power
P_s	Power Setting
P_{TX}	Transmit Power

3.3 Abbreviations

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

AIFS	Arbitration InterFrame Space
BER	Bit Error Ratio
BST	Beacon Service Table
BW	Bandwidth
CAM	Cooperative Awareness Message
CEN	Comité Européen de Normalisation
CEPT	Conférence Européenne des administrations des Postes et des Télécommunications
CF	Configuration
C/I	Carrier-to-Interference ratio
CVIS	Cooperative Vehicle-Infrastructure Systems
dBm	dB Milliwatt
DCC	Decentralized Congestion Control
DFT	Discrete Fourier Transform
dRSS	SEAMCAT parameter, desired Received Signal Strength
DSRC	Dedicated Short Range Communication
ECC	Electronic Communications Committee
EIRP	Equivalent Isotropic Radiated Power
EMSL	European Microwave Signature Laboratory
EN	European Norm
ETSI	European Telecommunications Standards Institute
iRSSblocking	SEAMCAT parameter, interfering received signal strength blocking

iRSSunwanted	SEAMCAT parameter, interfering received signal strength unwanted signal
JRC	Joint Research Center
IEEE	Institute of Electrical and Electronics Engineers
IPR	Intellectual Property Rights
ISO	International Standardisation Organisation
ITS	Intelligent Transport System
ITS-G5	acronym for the 5,9 GHz vehicular adhoc network PHY
LDC	Low Duty Cycle
LHCP	Left Hand Circular Polarized
MAC	Medium Access Control
N/A	Not applicable
OBU	OnBoard Unit
PHY	PHYsical (OSI layer)
RBW	Resolution Bandwidth
RF	Radio Frequency
RSU	RoadSide Unit
RX	Receive
SEAMCAT	Spectrum Engineering Advanced Monte Carlo Analysis Tool
SUT	System Under Test
SUV	Sport Utility Vehicule
TER	CEN DSRC Transaction Error Ratio
TS	Technical Specification
TX	Transmit
VBW	Video Bandwidth

4 CEN DSRC Tolling systems

4.1 Introduction

In this clause the main technical and operational characteristics of the investigated CEN DSRC tolling systems are depicted. The focus is on the deployment scenarios and the critical operational conditions where a potential interference from ITS-G5 systems might occur. A typical tolling zone geometry is depicted in figure 1 for a two lane scenario. The interference from an ITS-G5 system can only occur during the transaction between the Road Side Unit (RSU) and the On Board Unit (OBU) in the tolling zone. Another possible interference effect could be the wake up of the OBU from the power save mode initiated by ITS signals.

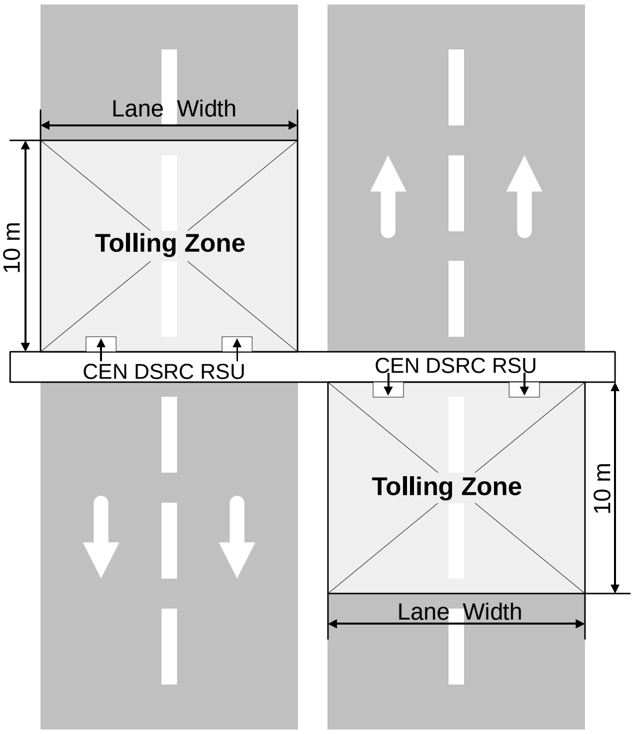


Figure 1: Typical tolling zone geometries for a two lane free flow scenario

Three main tolling station types need to be differentiated:

- Free-Flow tolling stations and enforcement stations with a maximum of 6 parallel lanes (typical 3 to 4 lanes in each traffic direction)
- Toll plazas with an automatic barrier with up to 40 parallel lanes (Typical around 10 to 20 lanes in each traffic direction)
- Toll plazas with automatic lanes (reduced speed) with up to 40 parallel lanes (typical around 1 to 10 lanes in each traffic direction)

Figure 2: Typical free-flow installation with three lanes

Figure 3: Typical toll plaza with an automatic barrier (left) and automatic lanes (right)

4.2 Technical Characteristics of the Road side Unit (RSU)

4.2.1 RF characteristics

Detailed characteristics are defined in table 1 (from TR 102 654 [i.4]).

Table 1: Parameters of a typical RSU

DSRC Road Side Unit (RSU)	Value	Units
Receiver bandwidth	500	kHz
Receiver sensitivity	-104	dBm
Antenna gain bore sight	13	dBi
Antenna gain outside RSU active angle (worst case as in [i.3])	-2	dBi
Antenna polarization	LHCP	
cross-polar discrimination, ellipticity of polarization	10	dB
TX output power level, EIRP	33	dBm
RSU mounting height above ground	2,5 to 7	m
Protection criterion (S/I)	6	dB
TX Frequency / Bandwidth	see clause 5.1 [i.4]	

4.2.2 Antenna

The RSU antenna is tilted downside for the interrogation of the onboard units. Outside of the main beam the antenna has reduced gain by a factor of around -15 dB [i.3]. The typical main beam e.i.r.p. is 33 dBm leading to an e.i.r.p of around 18 dBm outside of the main beam. A typical setup is depicted in figure 4. A large part of the 10 m tolling zone is covered by the main beam.

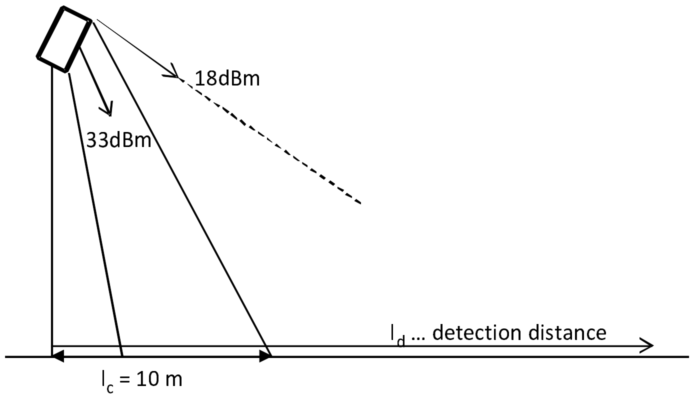


Figure 4: Typical Antenna characteristics of a RSU antenna

In a multilane set up with several parallel lanes a single RSU will cover more than a single lane. This leads to an overlap between two adjacent RSUs. By doing so, a better coverage can be guaranteed.

4.3 Technical Characteristics of the Onboard Unit (OBU)

4.3.1 RF characteristics

Detailed characteristics are defined in table 2 (from TR 102 654 [i.4]).

Table 2: Parameters of a typical OBU

DSRC On Board Unit (OBU)	Value	Units
OBU sensitivity (typical)	-60 to -50	dBm
Wakeup sensitivity	-60 to -43	dBm
Antenna polarization	LHCP	
cross-polar discrimination, ellipticity of polarization	6	dB
Car windscreen loss	3	dB
OBU mounting height above ground	1 to 2,2	m
Protection criterion (S/I)	10	dB
TX Frequency / Bandwidth	see clause 5.1 [i.4]	

4.3.2 Antenna

The typical antenna pattern of an CEN DSRC OBU in boresight is given in figure 5. This antenna pattern is the standalone OBU antenna pattern. The effective antenna patterns including the car attenuations will be presented in the result section of the present document.

In a passenger car the OBU is tilted, and bore sight is directed upwards. A measured azimuth (horizontal) antenna diagram for such a tilted OBU antenna is shown in figure 6.

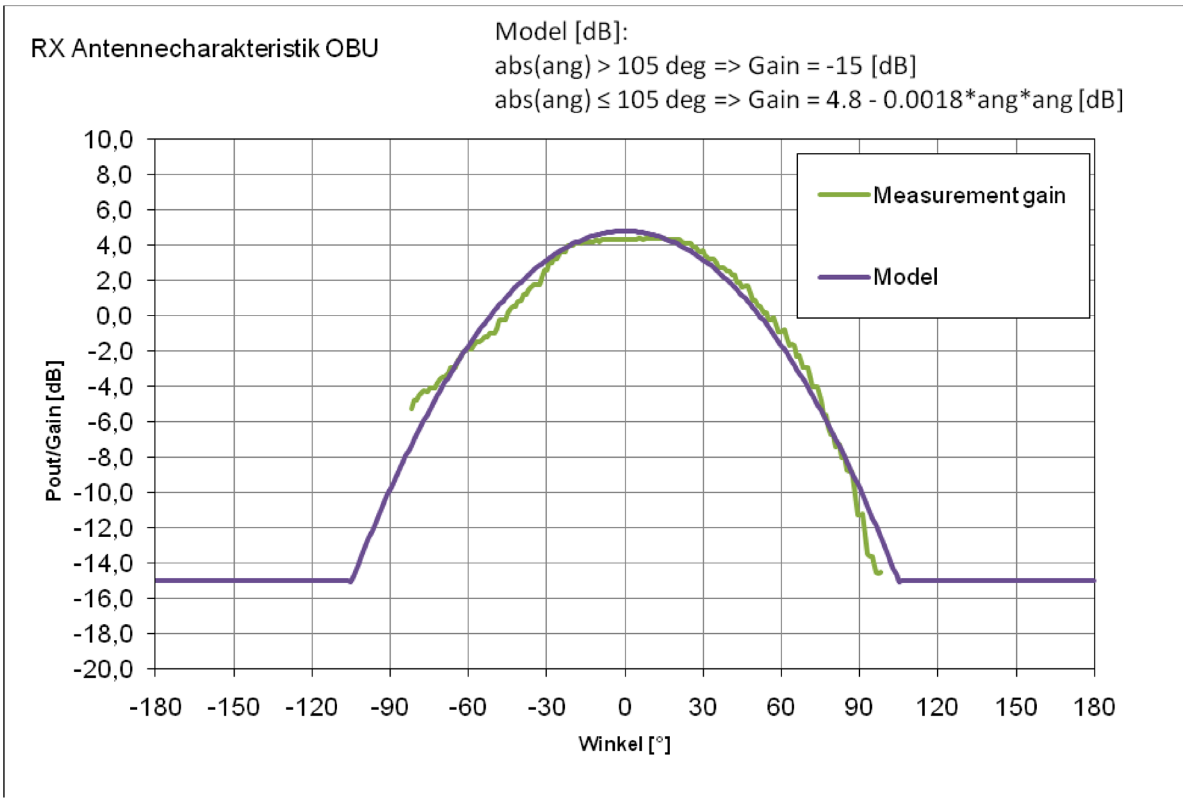


Figure 5: Typical isolated antenna pattern of a CEN DSRC On Board unit (OBU) in boresight

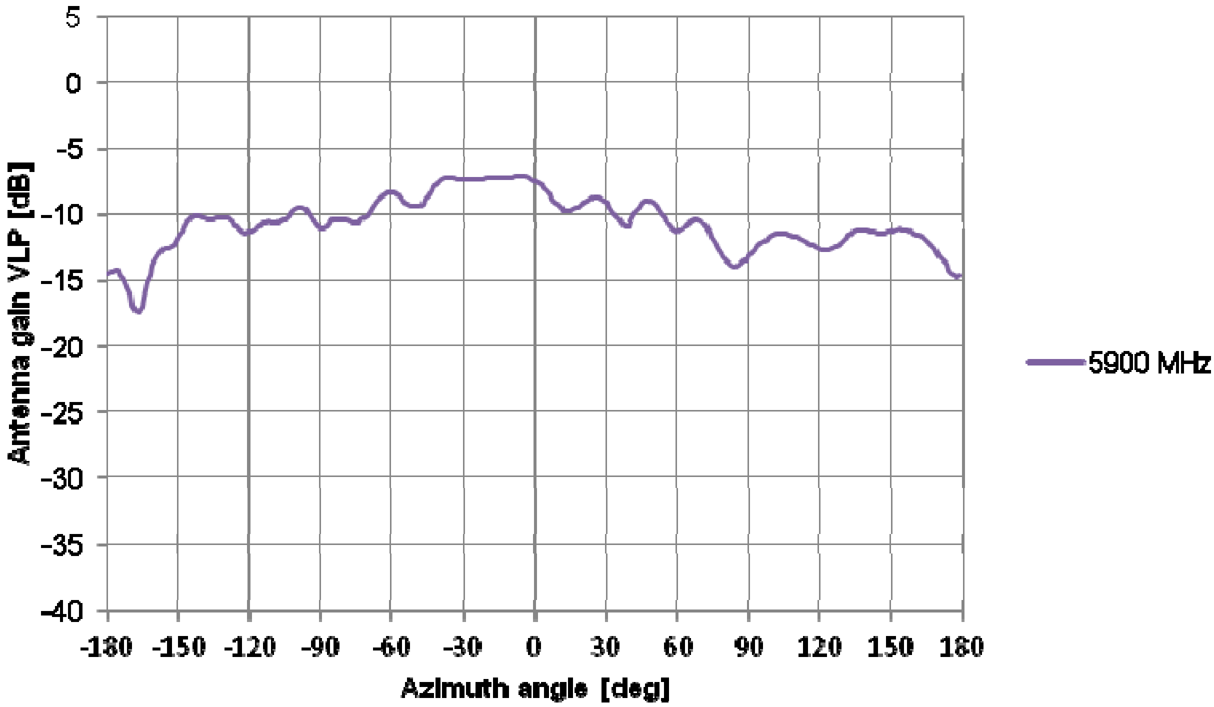


Figure 6: Typical isolated antenna pattern of a CEN DSRC On Board unit (OBU) tilted by 70° as usual when mounted in a passenger car

4.4 Protocol Layer

The basics of the timing of a CEN DSRC transaction are defined by CEN EN 12795 [i.1]. Timing details are application specific and different for each toll operator and toll station type (see clause 4.1). Additionally the OBU type can have an influence on the timing behaviour (e.g. the late response procedure as defined in CEN EN 13372 [i.2]).

The timing behaviour of a CEN DSRC transaction can be exploited to optimize the coexistence properties.

4.5 Interference from ITS-G5 stations

4.5.1 Physical layer

See ES 202 663 [i.5].

4.5.2 Protocol layer

See ES 202 663 [i.5] and the additional standards under development within ETSI TC ITS.

4.6 Conclusion

The presented technical characteristics and deployment scenarios of the two considered systems (CEN DSRC and ITS-G5) lead to the conclusion that coexistence in the same geographic area between the systems is possible only under certain restrictions on the ITS system. The present document will evaluate specific rules to guarantee this coexistence without harmful degradation of the systems' performance.

5 Coexistence Evaluation: Simulations

5.1 Introduction

The coexistence evaluation based on simulation should support the evaluation measurements in order to better understand the interference mechanism and especially the effect of a large number of independent interferers which cannot be evaluated in a real measurement without a large effort. In an initial step the simulations should confirm/verify the critical scenarios defined. The simulation results should then be used to evaluate the critical parameters in these scenarios, like the maximum allowed ITS TX power, number of devices or the critical activity factors of single devices and of the overall ITS system.

5.2 Simulation scenarios and model assumptions

5.3 Simulator 1: SEAMCAT

5.3.1 Overview

In order to introduce radio systems for transport systems (Intelligent Transport Systems - ITS) in the frequency range between 5,875 GHz to 5,905 GHz it is essential to ensure the coexistence with the already established electronic tolling systems (Dedicated Short Range Communication - DSRC), which are working in the frequency range between 5,795 GHz to 5,815 GHz. For estimation of the interference probability the simulation tool SEAMCAT is used. SEAMCAT (Spectrum Engineering Advanced Monte Carlo Analysis Tool) is freely available (www.seamcat.org) and a CEPT agreed software tool for studies regarding the interference between different radio communication systems.

Following traffic scenarios and simulation parameters were used for eight different simulation runs:

Traffic scenarios:

- Scenario I: One single interferer in the same lane at fixed position.
- Scenario II: One single interferer in the neighbour lane.
- Scenario III: Three lane heavy traffic scenario:
  - This scenario is used for calibration and consistency check of the SEAMCAT setup.
- Scenario IV: Seven lane congestion scenario:
  - A seven lane congestion scenario with different vehicle positions and TX duty cycles of the ITS-G5A stations.
- Scenario V: Seven lane very heavy traffic scenario:
  - A seven lane traffic scenario with different vehicle positions and TX duty cycles of the ITS-G5A stations.

Simulation parameters:

- With CEN DSRC OBU antenna diagrams derived from the measurements TD_CAL_01 and TD_COEX_OBU_01 (run 1, 2, 3,5 and 6).
- Different power levels:
  - ITS-G5 power level sweep from 0 dBm to 50 dBm;
  - Distinct ITS-G5 transmit power levels of 10 dBm, 15 dBm, 20 dBm, 25 dBm, 30 dBm and 33 dBm;
  - ITS-G5 TX power control.
- With ITS-G5 duty cycle values of 0,25 %, 0,5 %, 1 %, 2 %, 5 %, 10 % and 100 %.

The combination of these traffic scenarios and parameters used for each simulation run is summarized in table 3.

Table 3: SEAMCAT simulation test run overview

simulation number	traffic scenario	OBU antenna	ITS-G5 TX power level / dBm	ITS-G5 duty cycle %
1	I	TD_CAL_01	sweep 0 to 50	100
2	II	TD_CAL_01	sweep 0 to 50	100
3	III	TD_CAL_01	10	100
4	IV	TD_CAL_01	10, 15, 20, 25	0,25, 0,5, 1, 2, 5, 10
5	V	TD_CAL_01	10, 15, 20, 25	0,25, 0,5, 1, 2, 5, 10
6	IV	TD_CAL_01	power control range 25..50 m	1
7	V	TD_CAL_01	power control range 25 m to 100 m	1
8	IV	TD_CAL_01	10, 15, 20, 25, 30, 33 power control range 25 m to 250 m	1, 2
9	IV	TD_CAL_01	10, 15, 20, 25, 30, 33 power control range 25 m to 500 m	1, 2
10	IV	TD_CAL_01 TD_COEX_OBU_0 meas. run 1, 2, 3, 5, 6	10, 15, 20	1, 0,5, 0,25

5.3.2 Basic properties of SEAMCAT

For interference calculation, SEAMCAT uses a victim link between the victim receiver (which is the one of interest in terms of the interference) and its dedicated transmitter and one or more interference links. All these devices can be freely placed to define the intended scenario.

In the scenario diagrams, the communication partners are represented by coloured symbols as shown in figure 7.

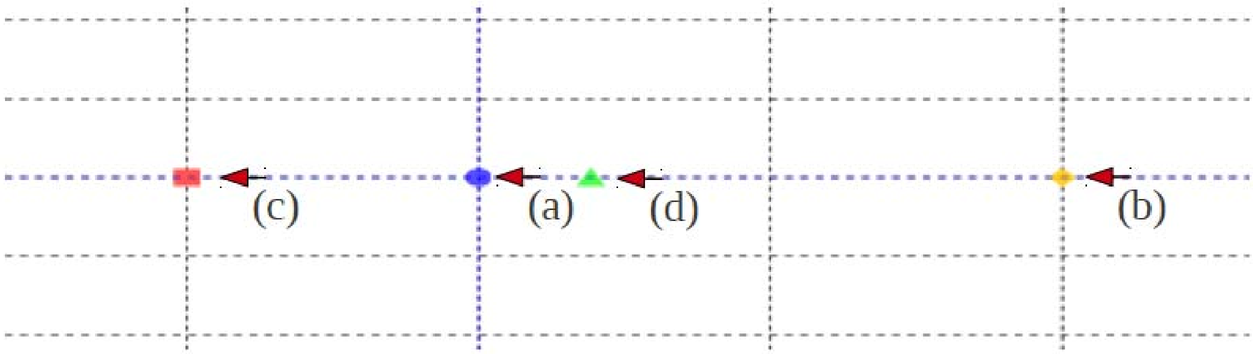


Figure 7: Simple scenario for reference and calibration

The transmitter of the victim link, i.e. the RSU (a), is placed in the origin and marked with a blue ellipse. The victim receiver, i.e. the CEN DSRC OBU (b), is marked with a yellow diamond. The red rectangles are the interfering transmitters, i.e. the ITS-G5 transmitters (c). The green triangles represent the receivers of the interfering transmitters (d). They are only needed for the simulation of the ITS-G5 transmit power control.

For the simulation of the interference between CEN DSRC and ITS-G5, the scenario will focus on a tolling station. Such a tolling station consists of several Road Side Units (RSU), each mounted above one traffic lane to communicate with an On-Board Unit (OBU), which is mounted behind the windscreen of passing by vehicles. For the simulations, it does not matter if we refer to free flow tolling stations or a tolling station with the need to slow down the vehicle speed.

5.3.3 Radio characteristics used in the SEAMCAT simulation

5.3.3.1 CEN DSRC OBU antenna characteristics

The antenna characteristics derived from measured data used for the SEAMCAT simulations are described in clause B.2.

5.3.3.2 ITS-G5 antenna characteristic

For the ITS-G5 interfering transmitters, an omnidirectional antenna characteristic is assumed.

5.3.3.3 CEN DSRC OBU receiver

The victim link, i.e. the link between CEN DSRC RSU and OBU, works at 5 805 MHz right in the middle of the DSRC band 5 795 MHz to 5 815 MHz, the reception bandwidth is set to 20 MHz. The blocking capabilities, i.e. the ability of the receiver to block signals outside the reception bandwidth, are set to a constant of 3 dB, thus reflecting the properties of the OBU receiver. The incident CEN DSRC signal power level at the OBU is fixed to -47 dBm (SEAMCAT parameter dRSS) and is therefore independent from the location of RSU and OBU.

A C/I value of 4 dB is assumed in all simulations. An interference event will occur when the ITS-G5 signal level at the OBU is larger than -51 dBm. This is based on TS 102 792 [i.7] which defines ITS-G5 transmit power levels, which should be tolerated by the OBU.

5.3.3.4 ITS-G5 emission mask

The interfering links operate at a centre frequency of 5 900 MHz (channel type G5CC according to ES 202 663 [i.5]), using an emission mask as shown in figure 8. The values of 0,0 dBm represent the ITS-G5A band 5 885 MHz to 5 905 MHz.

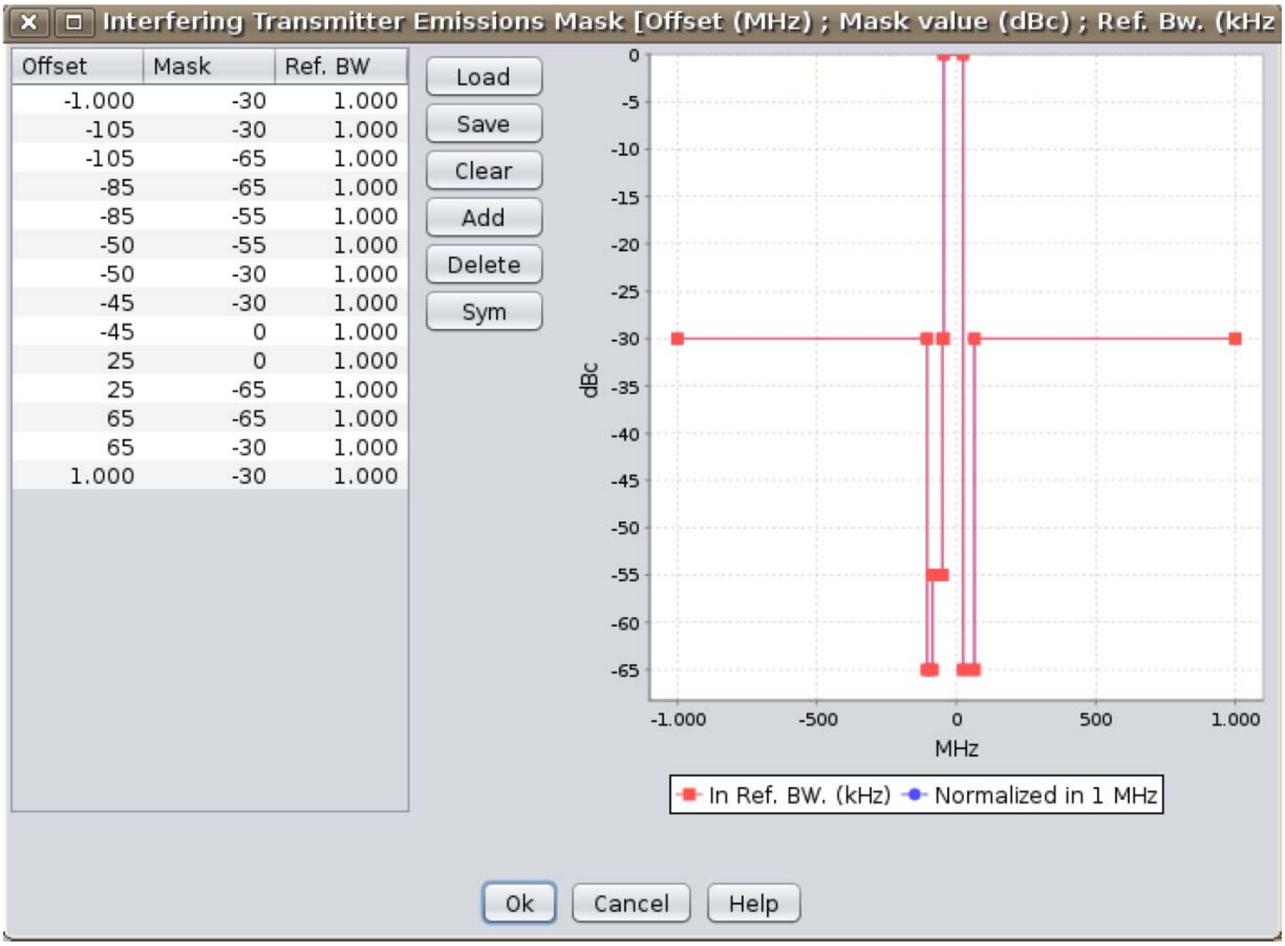


Figure 8: Emission mask of the interfering link (ITS-G5)

5.3.3.5 Radio channel model

The transmission path between CEN DSRC RSU and OBU is not of importance here, since the received signal strength is fixed to -47 dBm as mentioned in clause 5.3.3.3. The path between interfering transmitter(s) and CEN DSRC OBU is modelled with SEAMCAT's standard free space model. The path loss measured in dB was varied for each run, using a Gaussian distribution with a standard deviation of 1 dB. The same models is being used between the different ITS stations.

5.3.3.6 ITS-G5 transmission burst considerations

For ITS-G5 duty cycles below 100 % the SEAMCAT simulation setup was configured in such a way that it reflects the transmission of message bursts with considerable long pauses in between. This corresponds to the cyclic transmissions of CAM or other short repetitive ITS-G5 messages with a length of about 1 ms.

It does not cover occasional long lasting continuous data transfers. These data transfers would cause harmful interference to CEN DSRC OBUs whenever the incident power level exceeds the interference limit.

5.3.4 SEAMCAT Simulation Scenarios

5.3.4.1 Scenario I: One single interferer in the same lane at fixed position

An ITS-G5 interferer is placed 15 m in front of the CEN DSRC OBU at the same lane.

5.3.4.2 Scenario II: One single interferer in the neighbour lane

An ITS-G5 interferer is placed randomly in a range of -20 m to 20 m distance relative to the CEN DSRC OBU in an adjacent lane.

5.3.4.3 Scenario III: Three lanes heavy traffic

This scenario is used for calibration and consistency check of the SEAMCAT setup.

The transmitter of the victim link, i.e. the CEN DSRC RSU, is placed in the origin (a). The victim receiver, i.e. the CEN DSRC OBU (b), is placed in the same lane 10 m in front of the CEN DSRC RSU, as given by the CEN DSRC tolling zone geometry. One interferer, i.e. the ITS-G5 transmitter, is placed 30 m and one 15 m in front of the CEN DSRC OBU, another one is placed 15 m behind. This distance was chosen to reflect an averaged safety distance between moving vehicles. The positions of these three interferers were fixed for all simulation runs.

NOTE: The Austrian "Kuratorium für Verkehrssicherheit" gives a value of 1,33 s as an average safety distance on Austrian Motorways. Assuming a speed of 100 km/h, this value corresponds to a distance of nearly 37 m. Therefore, the 15 m set in the scenario is the worst case which might happen only very rarely.

Additionally, there are two neighbouring lanes with 3,5 m width as common on motorways. Every lane is populated with a platoon of three interfering transmitters, the distance between these transmitters is also 15 m. The positions of the whole platoon along the lane (horizontal axis in figure 9) in relation to the OBU are randomly set by the simulation tool within a range of ±20 m. Thus, figure 9 represents only the positioning for one single run.

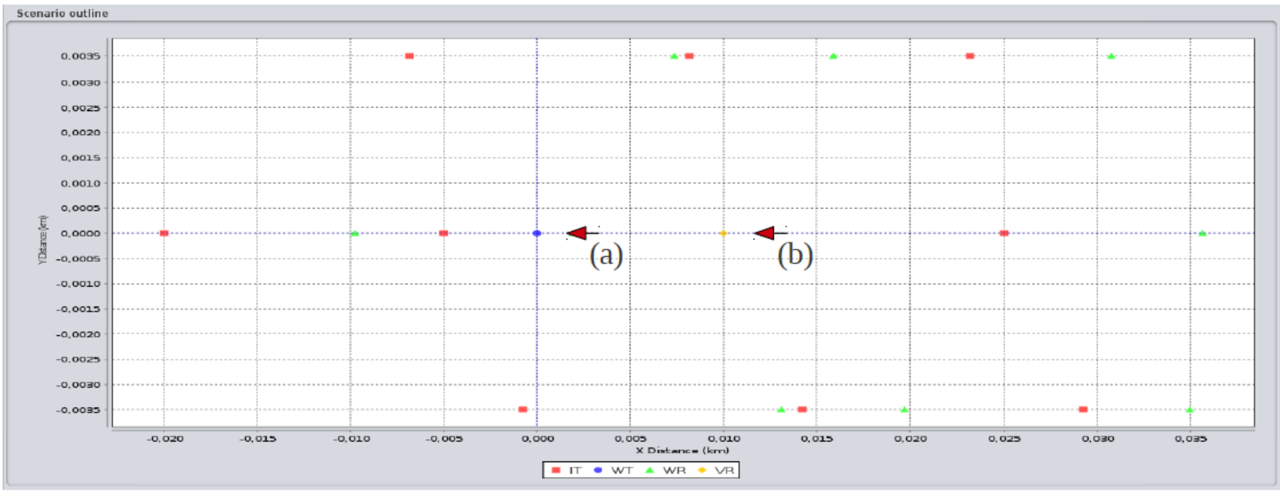


Figure 9: Simulation scenario I used for calibration and consistency check

The RSU is placed at a height of 6 m, The CEN DSRC OBU as well as the ITS-G5 transmitters are placed at a height of 2 m. Since there is no vertical antenna pattern used (see clause B.2.1), the height of the transmitters and receivers is not of importance in this simulation.

5.3.4.4 Scenario IV: Seven lanes congestion

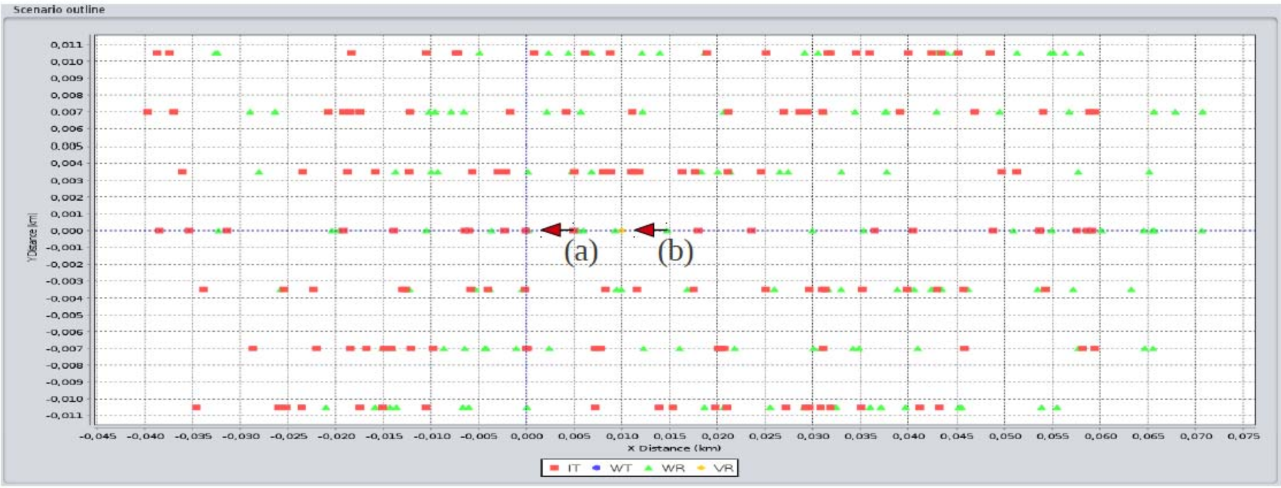


Figure 10: Simulation scenario II as SEAMCAT screen shot

In scenario II as depicted in figure 10, CEN DSRC RSU (a) and OBU (b) are placed in the same way as before, i.e. in a distance of 10 m. On both sides of the OBU are three lanes with 3,5 m width, each of them is randomly populated with 20 ITS-G5 transmitters in a range of ±50 m distance from the OBU. There are 10 ITS-G5 transmitters in front of and 10 ITS-G5 transmitters behind the OBU in the same lane, randomly spread over the same range as in the neighbouring lanes. The minimum distance between OBU and an ITS-G5 transmitter is 5 m. Hence, a total of 140 ITS-G5 transmitters is placed in every run of the simulation.

In average the ITS-G5 transmitters are placed in 5 m distance to each other, i.e. the cars stay bumper-to-bumper.

5.3.4.5 Scenario V: Seven lanes very heavy traffic scenario

In this scenario the setup is equivalent to scenario 2 as described in clause 5.3.4.4, but the traffic density was reduced by placing only 10 cars per lane and 5 in front and 5 behind the CEN DSRC OBU. This results in a total of 70 ITS-G5 transmitters per run and an average distance between the ITS transmitters of 10 m.

5.3.5 SEAMCAT simulation results

5.3.5.1 Simulation 1: Single interferer at same lane

SEAMCAT allows a separate variation of the transmission power of every single interfering transmitter in the scenario. Figure 11 shows the interference probability for an ITS station with 100 % duty cycle 15 m in front of the CEN DSRC OBU represented by a TD_CAL_01 antenna model (see clauses B.2.2 and 5.3.4.1 traffic scenario I). This probability represents the stochastic nature of the channel model used by SEAMCAT for 10 000 simulation runs.

One can observe that a transmission power level of 10 dBm for a single ITS station with 100 % duty cycle causes no harmful interference. An interference probability of 10 % would be reached for a TX power level of around 19 dBm.

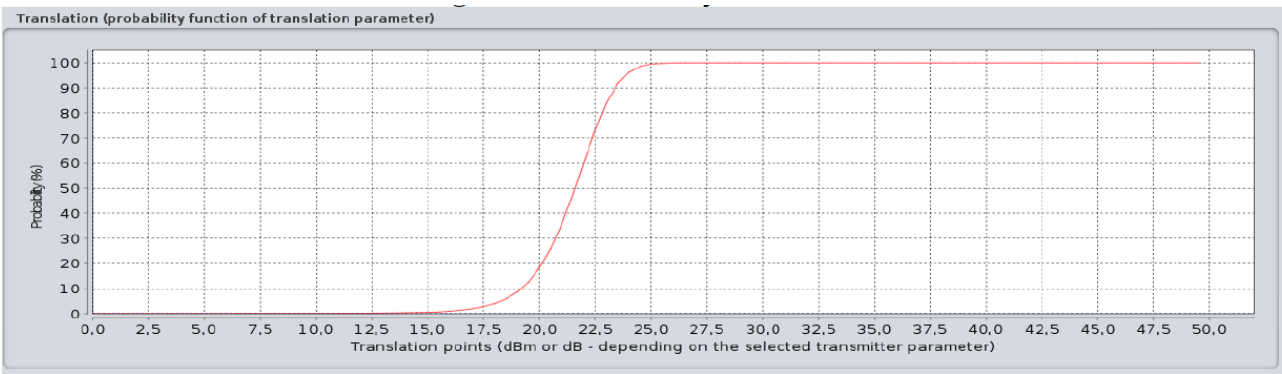


Figure 11: Interference probability for an ITS station with 100 % duty cycle 15 m in front of the CEN DSRC OBU (scenario I)

5.3.5.2 Simulation 2: Single interferer at neighbour lane

In figure 12 the results for traffic scenario II are depicted. The ITS station with 100 % duty cycle is placed on the neighbouring lane as described in traffic scenario 2 (clause 5.3.4.2). The CEN DSRC OBU antenna was modelled according to the TD_CAL_01 measurement results (see clause B.2.2).

In contrast to simulation 1, where the interfering transmitter is at the same location for every run of the simulation, in simulation 2 the transmitter is placed randomly for every run in a range between -20 m to 20 m in horizontal distance from the OBU. Therefore, the resulting probability distribution function is different, because the radio channel model and the distance are statistically independent stochastic processes and form a new compound probability process.

The probability distribution function depicted in figure 12 is not as smooth as the one depicted in figure 11. This is either because 10 000 simulation runs were not enough for a reasonable approximation of the real probability distribution function, or the probability distribution function of the resulting compound probability process has really several inflection points.

An ITS-G5 output power level of 10 dBm does still no harmful interference, but an interference probability of 10 % would be reached for an output power level of approximately 15 dBm. The practical relevance of this result is difficult to interpret, but one can imagine that this scenario II describes a vehicle that is overtaking. The total investigated relative distance is 40 m. An interference probability of 10 % can therefore be interpreted as a relative driving distance of 4 m where an overtaking vehicle with 15 dBm ITS-G5 output power level might cause harmful interference to the CEN DSRC OBU. Since both vehicles are moving while one is overtaking, the absolute driving distance is much higher, because it is given by the distance the overtaking vehicle moved while the other one moved 4 m less.

Simulation 1 and simulation 2 were also used to check the correctness of the settings and the models.

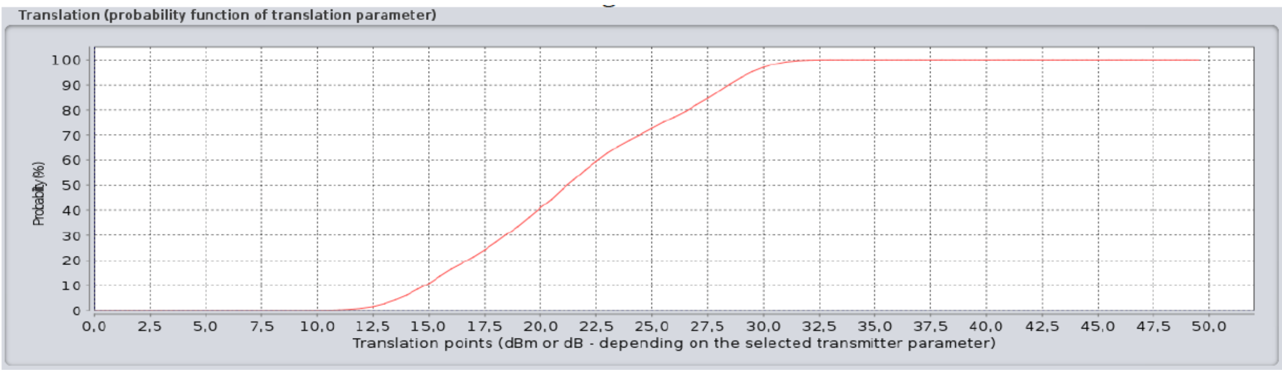


Figure 12: Interference probability for an ITS station with 100 % duty cycle at the neighbouring lane of the CEN DSRC OBU (scenario II)

5.3.5.3 Simulation 3: Three lanes heavy traffic

For this simulation according to traffic scenario III (see clause 5.3.4.3), the duty cycle was set to 100 %, i.e. every ITS G5 transmitter (9 ITS stations) placed in the scenario is transmitting all the time. The ITS-G5 transmission power level was set to 10 dBm. 10 000 events were generated. The CEN DSRC OBU antenna was modelled according to the TD_CAL_01 measurement results (see clause B.2.2).

For this setup the SEAMCAT parameter iRSSunwanted resulted in -104,68 dB. It is the part of the interferer's unwanted emission, which is within the receiver bandwidth of the victim receiver, i.e. the OBU, averaged over all simulation runs. This result is much below the interference power limit. Hence, the ITS-G5 unwanted emissions can be neglected.

For this setup the SEAMCAT parameter iRSSblocking resulted in -55,69 dBm. This value refers to the part of the interferer's transmitted energy, which is received by the OBU according to the blocking mask at the interferer's centre frequency from all interferers averaged over all simulation runs. This result has the same magnitude as the interference power limit. Since it is smaller than the limit, interference events will be seldom.

Simulation 3 results in an overall interference probability of 0,1 % only. This effect is mainly due to the superposition of the received interference at the CEN DSRC OBU coming from the 9 ITS-G5 station transmitting with 100 % duty cycle.

5.3.5.4 Simulation 4 and 5: Seven lanes, distinct power levels

For this simulation, the ITS duty cycle was varied in a value range from 0,25 % to 10 %. Therefore, the number of runs was increased to 50 000. Traffic scenario IV with 140 ITS transmitters and V with 70 ITS transmitters were used for simulation (see clauses 5.3.4.4 and 5.3.4.5).

A summary of the simulation setups and the results is given in table 4. The ITS station penetration rate is assumed to be 100 %, so that all mobile involved in the simulation are equipped with an ITS station. This simulation is performed with the distinct ITS-G5 TX power levels of 10 dBm, 15 dBm, 20 dBm and 25 dBm. Since the results for 25 dBm was already inacceptable for a proper CEN DSRC operation, the worst case with an ITS-G5 output power level of 33 dBm was not simulated any more.

Table 4: Interference probability for different ITS-G5 TX power levels and duty cycles for scenario IV and V

Transmit power level	Duty cycle	Scenario IV, 140 ITS transmitters: Probability of interference	Scenario V, 70 ITS transmitters: Probability of interference
10 dBm	0,25 %	0,00 %	0,00 %
	0,50 %	0,00 %	0,00 %
	1,00 %	0,00 %	0,00 %
	2,00 %	0,00 %	0,00 %
	5,00 %	0,05 %	0,00 %
	10,00 %	0,74 %	0,03 %
15 dBm	0,25 %	0,19 %	0,10 %
	0,50 %	0,50 %	0,26 %
	1,00 %	1,16 %	0,53 %
	2,00 %	3,24 %	2,14 %
	5,00 %	13,79 %	4,61 %
20 dBm	0,25 %	1,73 %	0,83 %
	0,50 %	3,68 %	1,78 %
	1,00 %	8,54 %	3,75 %
	2,00 %	19,65 %	8,31 %
25 dBm	0,25 %	6,39 %	3,18 %
	0,50 %	13,42 %	6,68 %
	1,00 %	26,05 %	12,79 %

The inclusion of the duty cycle was realised by means of a power distribution function defined in SEAMCAT. A user defined stair was used, switching the transmitter off by setting a transmission power of -100 dBm and on by setting a value as indicated in the table with the given probability. Using this probability function, SEAMCAT will than calculate for every single ITS transmitter in every single run, if the transmitter will transmit or not. In this way, the real behaviour can be simulated correctly.

5.3.5.5 Simulation 6 and 7: Seven lanes, ITS-G5 TX power control

To show the influence of power control on the interference probability, first tests were done using rough assumptions regarding the DCC parameters (see [i.8]).

As first assumption regarding the properties of ITS-G5 devices, a minimum received power level at the ITS-G5 receiver of -85 dBm, a dynamic range of the ITS-G5 transmit power level of 30 dB, and a discrete power controller with a step size of 2 dB were supposed. As maximum TX power level, the initial value set for the simulation was used. The minimum transmission power level is thereby given by the initial power value reduced by the dynamic range.

For the power control simulation it was assumed that each ITS-G5 device will communicate to 100 other ITS-G5 devices. According to the density of the ITS-G5 stations, the transmission power level was adapted by SEAMCAT to have approximately that number of devices within the radio range, by ensuring at least the minimum power level (i.e. -85 dBm) at each intended receiver. Caused by the stochastic variation of the radio channel model, the number of receiving ITS-G5 stations could vary for each simulation run.

Since SEAMCAT cannot simulate this broadcast assumption directly, an ideal power control was simulated for point to point communications to all receivers in a certain distance range to the transmitter. Since in the end all results are averaged, the overall mean output power level is equivalent to the assumed broadcast power control value, when the distance range is set, such that according to the vehicle density approximately 100 vehicles are within this range.

The results are calculated based on the radio link configuration of the scenario. The transmission power necessary to ensure the minimum threshold for the received power at the intended receiver of each transmitter is calculated by the simulation tool according to the distance between the interfering transmitter and the intended receiver. For placement, the distance range around the ITS-G5 transmitter is taken into account and the concrete position is randomly chosen by SEAMCAT following a uniform distribution. The placement is done in the same traffic lane, which is no restriction due to the omnidirectional antennas used for the ITS-G5 transmitters.

In simulation 6 scenario IV with 140 ITS-G5 transmitters in an area of 30 m ×100 m around the reference CEN DSRC OBU position were used (see clause 5.3.4.4). For every ITS-G5 transmitter a receiver was placed randomly in a distance range from 25 m to 50 m.

Simulation 7 was done using scenario 5 with the reduced number of 70 ITS-G5 transmitters (see clause 5.3.4.5). Here the ITS-G5 receivers were placed in a distance range from 25 m to 100 m.

In both simulations, the initial values of 25 dBm transmission power and 1 % duty cycle were used. The CEN DSRC OBU antenna was modelled according to the TD_CAL_01 measurement results (see clause B.2.2). The simulations were done with 50 000 runs each. For comparison, each setup was also simulated with a fixed ITS-G5 output power level of 25 dBm.

All results of simulation 6 and 7 are summarized in table 5.

Table 5: Interference probability using TX power control at the ITS-G5 stations for scenario IV and V

Initially: Tx power 25 dBm, duty cycle 1 %	Probability of interference with fixed power level of 25 dBm	Probability of interference with power control
140 ITS transmitters (scenario IV), receivers within 25 m to 50 m	26,05 %	0,0 %
70 ITS transmitters (scenario V), receivers within 25 m to 100 m	12,79 %	0,0 %

As expected, it is shown that by means of power control the probability of interference can be significantly reduced, even when taking into account that the values used for this simulation are first assumptions only. The reason for this improvement is that the ITS-G5 transmit power level is strongly reduced by the power control. The total power reduction is dependent on the power control algorithm. A prove whether the algorithm used for the power control simulations is in line with the power control algorithms that will be implemented in real ITS-G5 stations was left open.

The presented scenarios would lead to a ITS-G5A channel load of around 100 %.

5.3.5.6 Simulation 8 and 9: Seven lanes, comparison between distinct power levels and ITS-G5 TX power control for different duty cycles

In simulation 8 scenario IV with 140 ITS transmitters in an area of 30 m × 100 m around the reference CEN DSRC OBU position were used (see clause 5.3.4.4). For every ITS-G5 transmitter a receiver was placed in a distance range from 25 m to 250 m.

Simulation 9 used the same setup as simulation 8 except the ITS-G5 receiver placement range was altered to 25 m to 500 m.

The simulations were done with 50 000 runs each. The power control was configured as described in clause 5.3.5.5 for simulation 6 and 7. The CEN DSRC OBU antenna was modelled according to the TD_CAL_01 measurement results (see clause B.2.2)

All results of simulation 6 and 7 are summarized in table 6.

Table 6: Scenario IV, comparison of Power Control, fixed power levels and different duty cycles

Initial Tx power and duty cycle	Probability of interference without power control	Probability of interference with power control, range 25 m to 250 m	Probability of interference with power control, range 25 m to 500 m
10 dBm, 1 %	0,00 %	0,00 %	0,00 %
10 dBm, 2 %	0,00 %	0,00 %	0,00 %
15 dBm, 1 %	0,03 %	0,00 %	0,01 %
15 dBm, 2 %	0,08 %	0,00 %	0,03 %
20 dBm, 1 %	0,29 %	0,00 %	0,04 %
20 dBm, 2 %	0,64 %	0,00 %	0,08 %
25 dBm, 1 %	1,31 %	0,00 %	0,04 %
25 dBm, 2 %	2,56 %	0,00 %	0,06 %
30 dBm, 1 %	3,04 %	0,00 %	0,03 %
30 dBm, 2 %	6,04 %	0,00 %	0,09 %
33 dBm, 1 %	4,64 %	0,00 %	0,05 %
33 dBm, 2 %	9,20 %	0,00 %	0,09 %

As expected, it is shown that by means of power control the probability of interference can be significantly reduced, even when taking into account that the values used for this simulation are first assumptions only. It should be explicitly mentioned here that the resulting TX power is determined only according to the random distance between ITS transmitter and receiver.

5.3.5.7 Simulation 10: Seven lanes congested, comparison of different OBU types

To verify the correctness of the antenna model according to the TD_CAL_01 measurement results, used in simulations 1 to 9, simulation 10 was performed using scenario IV (see clause 5.3.4.4). Three ITS-G5 parameter sets were used to compare the TD_CAL_01 antenna pattern with five other antenna patterns, which were extracted from the BER measurements (see clause B.2). All antenna patterns presented in clause B.2 were normalised for comparison in table 7.

Table 7: Comparison between different antenna models generated from measurement results

Tx power and duty cycle	Antenna pattern	scenario IV, 140 ITS transmitters Probability of interference
10 dBm, 1 %	TD_CAL_01	0,00 %
	OBU2	0,01 %
	OBU6	0,00 %
	OBU9	0,00 %
	OBU10	0,00 %
	OBU11	0,00 %
15 dBm, 0,5 %	TD_CAL_01	0,26 %
	OBU2	0,55 %
	OBU6	0,40 %
	OBU9	0,00 %
	OBU10	0,11 %
	OBU11	0,11 %
20 dBm, 0,25 %	TD_CAL_01	1,73 %
	OBU2	1,33 %
	OBU6	0,14 %
	OBU9	0,31 %
	OBU10	0,71 %
	OBU11	0,92 %

The TD_CAL_01 model evaluated from the substitution antenna measurement results, represents a conservative pattern, which results in general in an higher interference probability compared to the results obtained from antenna patterns deduced from BER measurements done on several different OBU types.

5.3.6 Interpretation, Conclusions and Outlook

Summarising the simulation results, it was shown that ITS-G5 transmissions can cause harmful interference to CEN DSRC devices. It was also shown that the ITS-G5 output power level and the duty cycle modify the severity of this threat. But the simulation setups could not model reality precise enough to define exact rules how to set these two parameters to ensure coexistence of ITS-G5 and CEN DSRC in a normal operation environment. Further simulations in conjunction with the measurement results are necessary to define these coexistence limits and rules.

In simulations 1, 2 and 3 100 % duty cycle of the ITS-G5 transmitters were considered by scenarios I, II and III. These scenarios with a few ITS-G5 stations using the whole channel bandwidth are not foreseen in real ITS-G5A systems. Nevertheless, they confirm the theoretical sensitivity figures developed in TR 102 654 [i.4] and they were used to calibrate and prove the SEAMCAT simulation setup.

Simulations 1, 2 and 3 show that there will be no harmful interference to CEN DSRC OBUs for ITS-G5 output power levels below 10 dBm.

From simulation 2 the interference range for overtaking vehicles can be deduced. The driving distance where harmful interference can happen in such an overtaking scenario depends on the ITS-G5 output power level and the driving speed of both vehicles.

EXAMPLE: Overtaking scenario based on simulation 2 results:
For an ITS-G5 output power level of 15 dBm and vehicle speeds of 120 km/h and 130 km/h the driving distance where harmful interference can happen results to 48 m for the slower vehicle and 52 m for the faster one.

The presented simulations using scenario IV are typical for a free flow tolling operation in a traffic jam condition, which has been identified as critical situation. The tolling operation in all simulation cases is performed at the sensitivity limited of the tolling link. A more realistic simulation could take a certain distribution of the link quality based on the equivalent incident CEN DSRC power level at the OBU as described in clause 6.3.1.3.1 into account.

In all simulation settings an ITS penetration rate of 100 % has been assumed. For penetration rates like 20 % as assumed in the year 2020 the results will be more relaxed.

Most parameters used for these simulations where taken from ETSI standards or drafts of such standards, like values for frequencies and transmission power levels or received signal strengths. Some of the assumptions made in the scenarios are quite pessimistic. E.g. the traffic density on the road will be more relaxed under free-flow operation. Others are likely too optimistic, e.g. the strong power reduction by the power control algorithm used for simulation. These assumptions should be kept in mind when rating the results.

By means of power control a substantial reduction of the interference probability can be achieved, as shown in the simulations. The needed parameter of the power control algorithm need to be included into the DCC definition and should be further proved whether they can be applied to real implementations of ITS-G5 devices (see [i.8]).

When using an ITS-G5 transmit power control, more sensitive ITS receivers will offer a reduction of the interference probability since the required RX power at the ITS receiver will be further decreased.

Toll plazas are tolling stations where vehicles reduce the speed or even have to stop. For these scenarios following effects need to be taken into account:

- The density of vehicles and therefore also the density of interfering transmitters will rise as well as the minimum distance to the OBU. Therefore, at the first view the interference probability will increase in comparison to the moving traffic. The scenario IV with 140 ITS-G5 stations in a range of 100 m can be seen as a worst case for such a situation.
- In this situation the number of interferer behind the tolling area is usually higher than in front of it, since the vehicles are leaving the toll plaza at high speed. Therefore, a simulation of this situation should have a higher ITS station density on the back side and a much lower on the front side of the reference vehicle.
- When using ITS-G5 power control, the ITS-G5 devices will reduce their transmission power, in order to control the load of the channel using the DCC algorithm (see [i.8]). This will limit the increase of interference probability for the tolling system.
- As part of the DCC algorithm, the duty cycle of the ITS-G5 devices will be reduced below the usual value. This will limit the interference probability for the tolling system, compared to a fixed duty cycle.
- Due to the slow movement of the CEN DSRC OBU, the time available for executing the tolling transaction will increase (e.g. 10 km/h will result in roughly 3,5 s). This time span makes the tolling system more robust in terms of interference, since more CEN DSRC frame retransmissions are possible compared to a free flow tolling station.

5.4 Simulator 2: CEN DSRC protocol simulator

5.4.1 Simulator 2: Basic properties

5.4.1.1 Simulator 2: Overview

This simulator was designed to investigate the behaviour of the CEN DSRC retry mechanism when interference by cyclic ITS-G5 messages (e.g. CAM) occurs. The timing and the transmit power level of these cyclic ITS-G5 messages can be configured (see also clause 6.3.3.1 and figure 85).

A straight motorway with a tolling station at position x = 0 m is used as scenario. Where the lane number, width, and length can be configured. The vehicle speed can be configured per lane, the vehicle distance is defined by the time in between moving cars.

The tolling zone is modelled by simulation of the CEN DSRC BER when passing through a toll station. The BER is calculated from a semi empiric model that takes the CEN DSRC RX power level and the interference signal into account. The CEN DSRC RX power level is calculated from the toll station geometry and the OBU mounting geometry by an empiric antenna model of OBU and RSU and a free space channel model. The interference signal is calculated from the interferer TX power level and the distance to the interferer from a free space model with a configurable path loss coefficient (see clause B.2 of [i.7]), it also takes a measured OBU interference susceptibility pattern into account. The windscreen attenuation is considered for both the CEN DSRC signal and the ITS signal.

The CEN DSRC timing including the "late response" behaviour and the frame types of the transaction can be configured. The simulator takes care of frame retransmissions invoked by frame errors in up or down link.

The simulator consists of following parts:

- RF simulator:
  - Includes antenna models and radio propagation models (all based on measurements).
- ITS-G5 Broadcast MAC layer simulator:
  - Simulates the behaviour of cyclic ITS-G5 broadcast messages for IEEE 802.11 [i.10] CSMA/CA.
- CEN DSRC protocol simulator:
  - Simulates the CEN DSRC transaction including retries, late response, and multiple OBUs.
- CEN DSRC frame error evaluation:
  - The values provided by the RF simulator determine, by an empiric model, the CEN DSRC frame error probability.
- Mobility simulator:
  - Moves the cars and defines the street geometry.

The interconnection between these parts is depicted in figure 13.

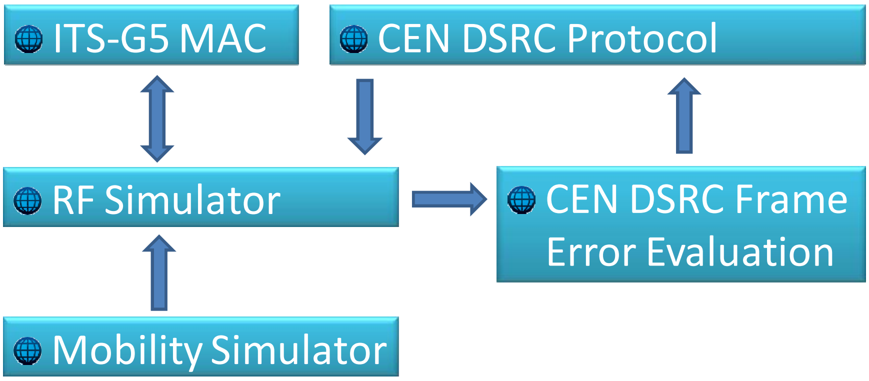


Figure 13: Simulator 2 architecture

5.4.1.2 Simulator 2: Configuration

5.4.1.2.1 Simulator 2: Configuration overview

The simulator setup is done in several dialog windows. These windows are grouped into following parameter categories:

- ITS-G5 configuration
- Mobility simulator configuration
- CEN DSRC OBU configuration
- CEN DSRC RSU configuration
- CEN DSRC transaction configuration

A comprehensive list of all configuration parameters is given in clause C.1.

5.4.1.2.2 ITS-G5 configuration

All simulation results presented in the present document were computed with following ITS-G5 MAC / PHY parameters:

- AIFS = 58 µs
- aSlotTime = 13 µs
- CW_{min} = 3
- Message life time = 10 ms
- Carrier sense level = -85 dBm
- RX Sensitivity = -85 dBm

The path loss coefficient was set to 1,8.

The message repetition rate, the frame length and the ITS-G5 TX power level were varied.

5.4.1.2.3 Mobility simulator configuration

The mobility simulator configurations used for all simulations are summarized in table 8.

The "calibration" scenario was used to reproduce Measurement 2 (clause 6.3.3).

The scenarios "One lane", "Two lanes" and "Three lanes" were used to evaluate the impact of different numbers of interferers.

All other scenarios describe more or less real traffic situations with different vehicle speeds at each lane.

Table 8: Overview of the mobility simulator configurations

Scenario name	Lanes	Vehicle speed in km/h	Number of cars	Distance between cars	Reference
Calibration	1	0	1	--	
One lane	1	29	2 to 12	2 s	
Two lanes	2	29	2 to 40	1,5 s	
Three lanes	3	29	3 to 15	1,5 s	
Slow traffic	8	27 to 32	397	1 s (7,8 m to 8,9 m)	Figure 14
Fast traffic	8	2 x 80 2 x 100 2 x 130	130	1 s (22 m; 28 m; 36 m)	Figure 15
Toll plaza	16	26 to 32,5	815	1 s (7 m to 9 m)	Figure 16
Light traffic	8	123 to 130	40	2,5 s (85 m to 90 m)	Figure 17
Truck scenario	8	77,5 to 81	186	1 s (~22 m)	Figure 18

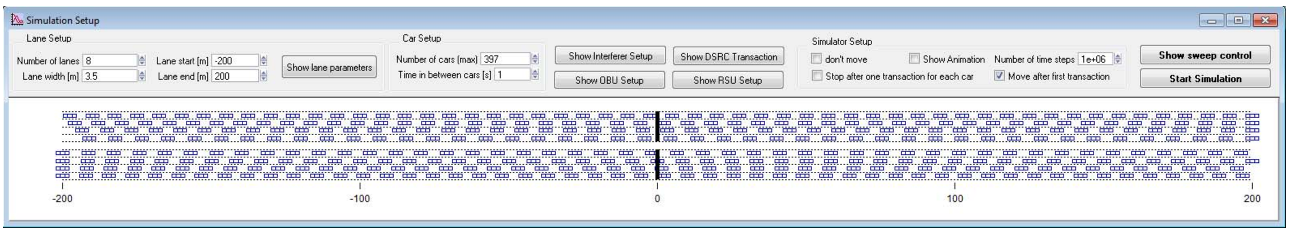


Figure 14: Slow traffic mobility simulator setup

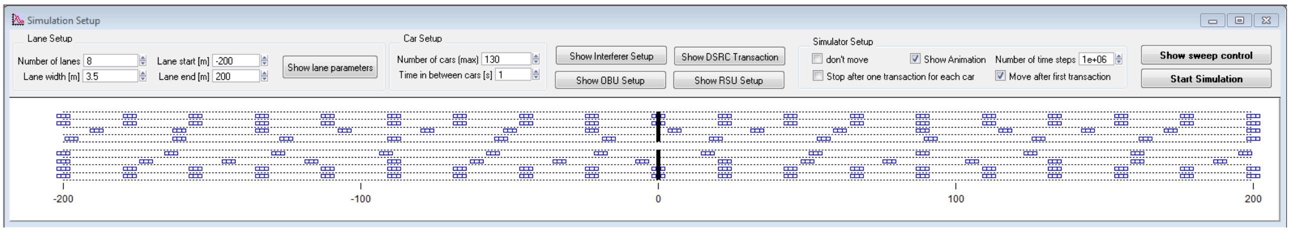


Figure 15: Fast traffic mobility simulator setup

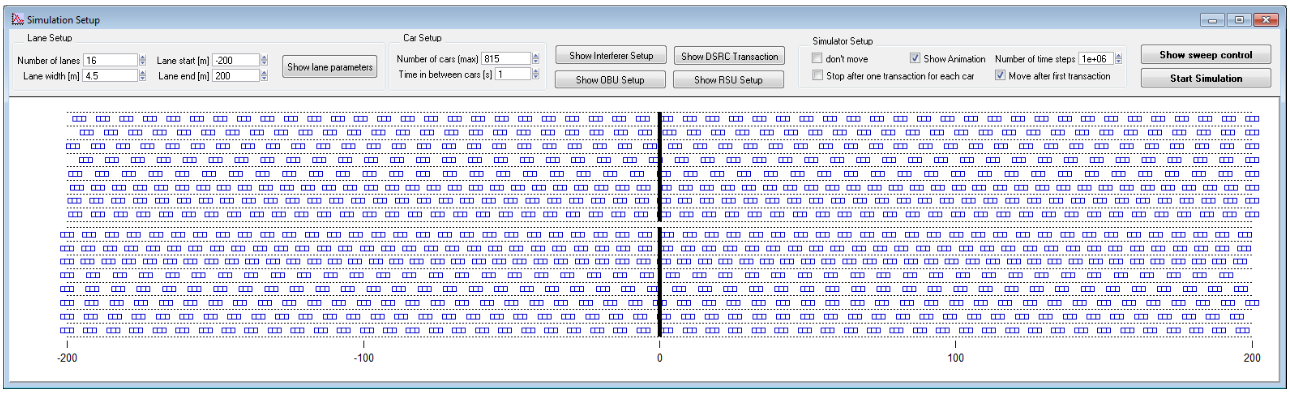


Figure 16: Toll plaza mobility simulator setup

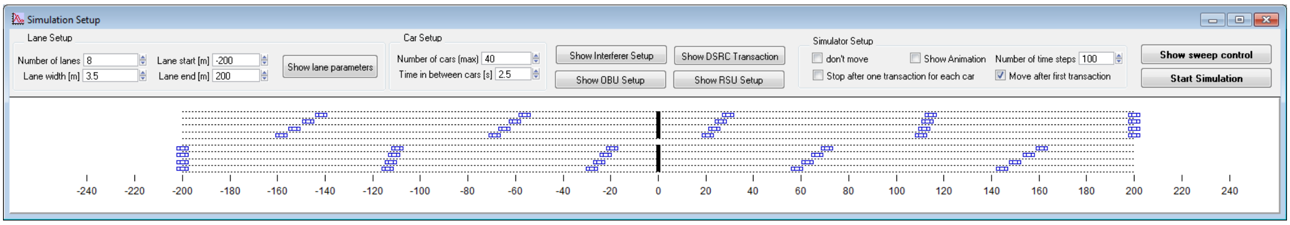


Figure 17: Light traffic mobility simulator setup

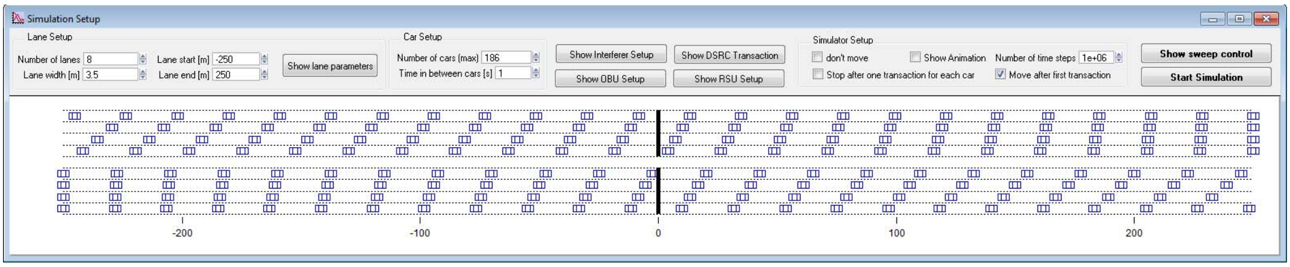


Figure 18: Truck scenario mobility simulator setup

5.4.1.2.4 CEN DSRC OBU configuration and CEN DSRC transaction configuration

Based on the measurement results reported in clause 6.3, OBU 6, 9, 10 and 12 were simulated.

Details of the OBU simulator setup are shown in clause C.2.

5.4.1.2.5 CEN DSRC RSU configuration

A standard CEN DSRC RSU was used for all simulations. The simulation parameters are shown in figure 19.

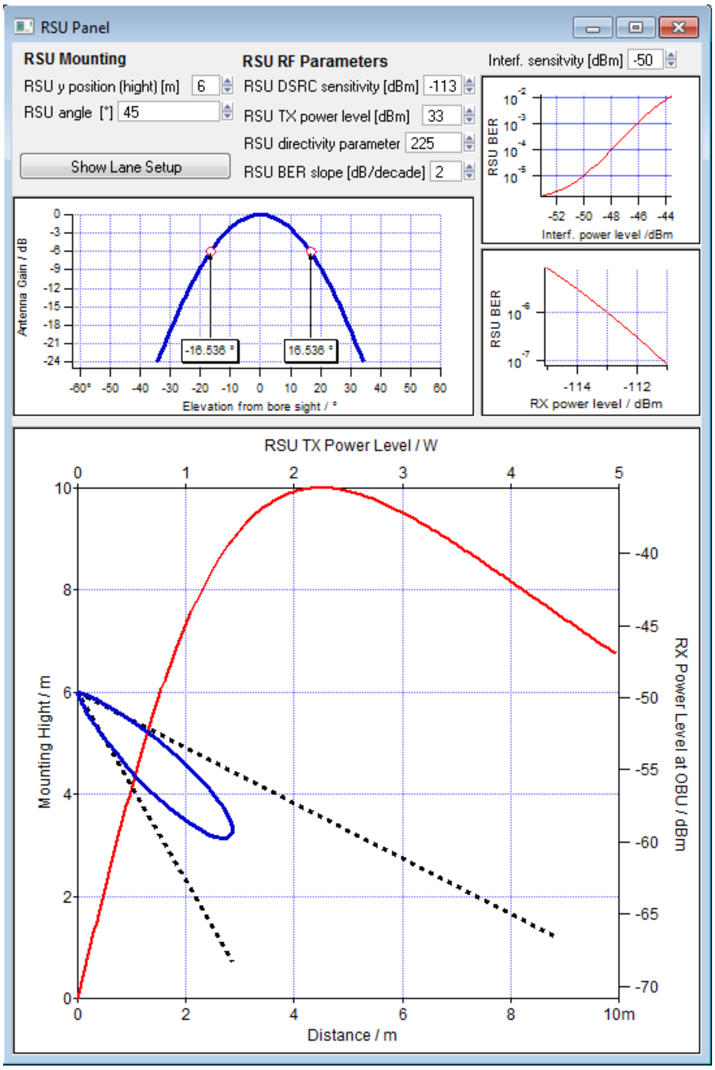


Figure 19: RF, BER and interference susceptibility simulation parameters for CEN DSRC RSU

5.4.2 Simulator 2: Simulation scenario overview

The performed simulations can be grouped in three parts:

- Calibration and test of the simulator:
  - These simulations were done to evaluate the correctness of the CEN DSRC protocol simulator.
- Determination of the impact of several interferers using LDC:
  - These simulations show the impact of the number of interferers and the idle time T_{off} on the number of broken CEN DSRC toll transactions for the ITS-G5 transmission time spans T_{on} = 1 ms, 2 ms, 3 ms, 5 ms.
- Simulation of realistic traffic scenarios:
  - For these simulations the parameters T_{on}, T_{off}, and P_{Tx} were swept to find advantageous configurations under different realistic traffic scenarios.

The simulations were performed for four different OBU types (see clauses 5.4.1.2.4 and C.2), for nine traffic mobility scenarios (see clause°5.4.1.2.3) and for the T_{on}, T_{off}, and P_{Tx} ranges listed in table 9. Where the duty cycle of one interferer was specified by the time span with active transmission T_{on} at a power level of P_{Tx} and by the time span T_{off} when the ITS-G5 was idle (see also figure 85). The case with low power transmissions (< 10 dBm) in between the active time slots was not investigated.

Table 9: Overview of the performed simulations

Type	OBU Type	Scenario	T_{on} / ms	T_{off} / ms	P_{Tx} / dBm
Calibration	OBU10 OBU12	Calibration	0,176 to 10	10 to 200	33
Number of potential interferers	OBU9	One lane Two lanes Three lanes	1 1, 2, 3, 5 1	50 to 1 000 30 to 2 000 50 to 1 000	330
	OBU10	Two lanes Three lanes	1	50 to 1 000	330
Realistic traffic scenarios	OBU6 OBU9 OBU10 OBU12	Slow traffic	1 to 10	50 to 2 000	15 to 33
	OBU10 OBU12	Fast traffic	1 to 10	50 to 2 000	15 to 33
	OBU6 OBU9 OBU10 OBU12	Toll Plaza	1 to 10	50 to 2 000	15 to 33
	OBU10	Light traffic	1	50 to 150	15 to 27
	OBU6 OBU9	Truck scenario	1 to 10	50 to 2 000	15 to 33

5.4.3 Simulator 2 results: Calibration

The "calibration" simulation was used to compare the results with Measurement 2 (clause 6.3.3) for validation of the CEN DSRC protocol simulator.

Figures 20 and 21 show for OBU10 and OBU12 the results for the average number of retransmissions per transaction for different T_{on} and T_{off} values. The measurement results are marked by symbols, the simulation results are shown as solid line.

The simulation results fit quite well to the measurement results.

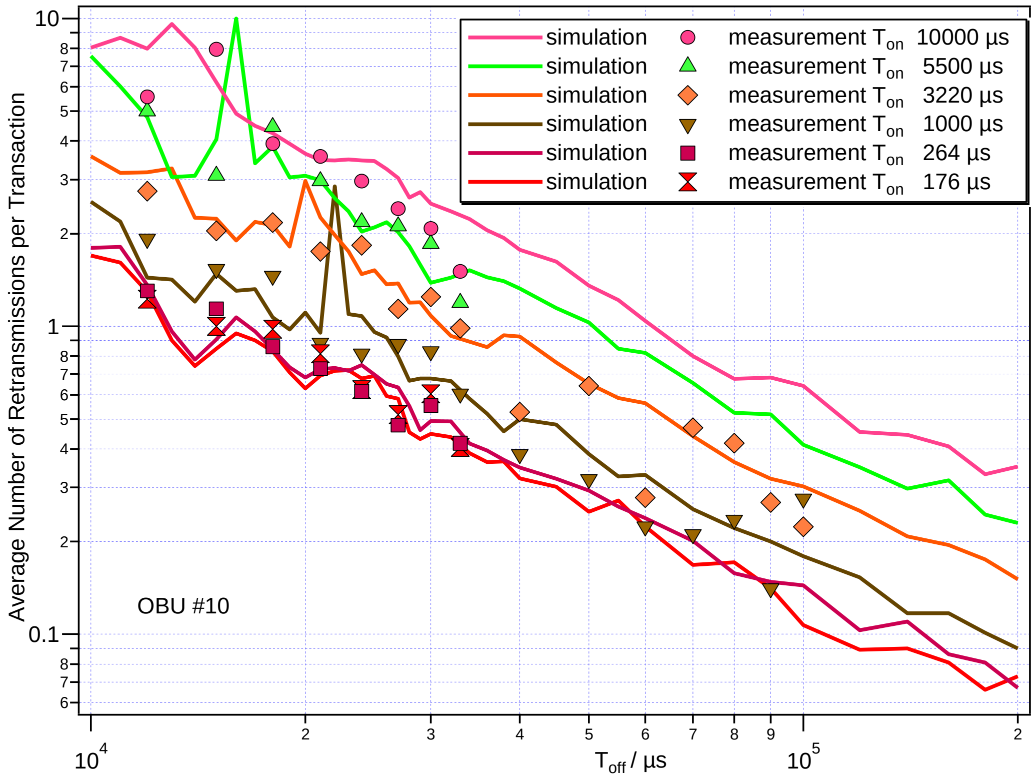


Figure 20: Comparison of results obtained for OBU10 with Simulator 2 and Measurement 2

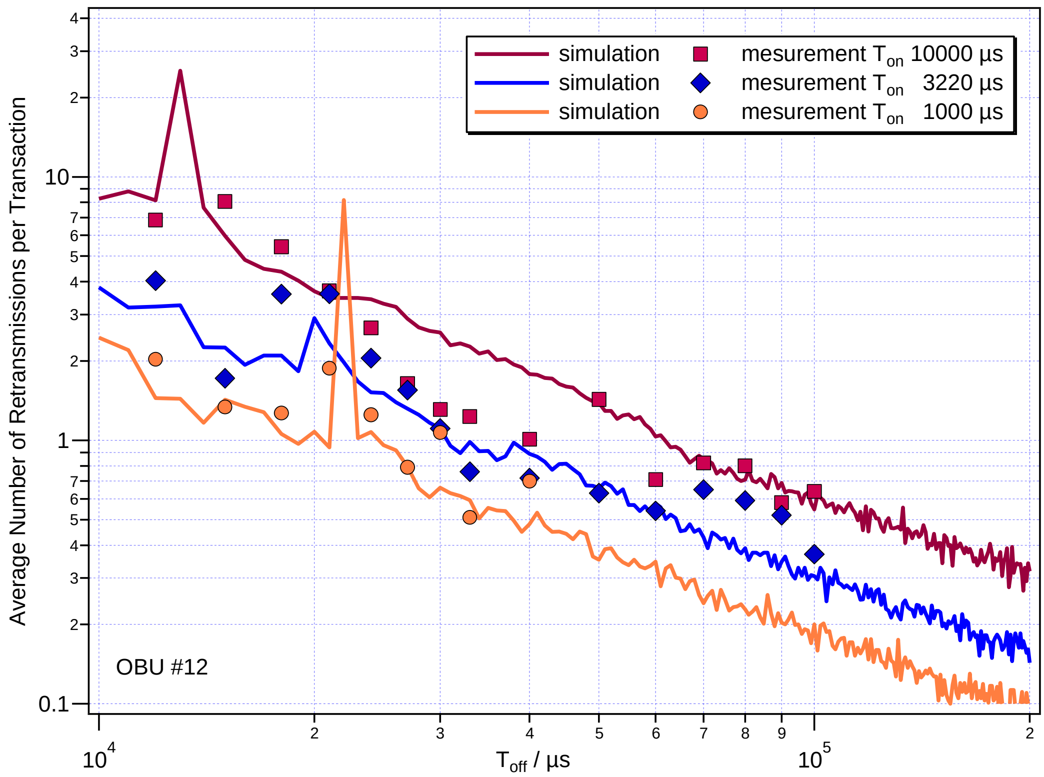


Figure 21: Comparison of results obtained for OBU12 with Simulator 2 and Measurement 2

5.4.4 Simulator 2 results: Evaluation of LDC parameters

5.4.4.1 Simulation details

The purpose of this simulation was to find the LDC parameter T_{off} (idle time) necessary to avoid harmful interference as function of the number of interferers and the ITS-G5 transmission time T_{on}.

To find this T_{off} time, a Monte Carlo analysis of scenarios with different number of cars and different ITS-G5 transmission times T_{on} and random time offsets between the transactions and the cyclic ITS-G5 transmissions was performed. The ITS stations used the IEEE 802.11 [i.10] broadcast MAC to avoid collisions of the cyclic transmissions that were each started with a random time offset. The CEN DSRC simulation used a realistic retransmission timing to recover disturbed data frames.

As setup slow moving ITS-G5 stations were used that transmit with a very high ITS-G5 output power level, so that they always interfere with the CEN DSRC OBU and the CEN DSRC RSU. Since the simulated vehicles were moved only with a speed of 29 km/h the influence of the BER when crossing the communication zone was not equivalent to a fast crossing. But this simplification reduced the computational effort of the transaction length statistics drastically. Otherwise a simulation run for each speed would have been necessary. From the transaction length statistics a cumulative broken transaction ratio was evaluated for different virtual vehicle speeds.

As criteria for harmful interference, the number of broken transactions was evaluated for different virtual driving speeds. If the simulated transaction time exceeded 80 % of the time span that the passage of the communication zone would last for a certain speed, the transaction was counted as broken. For a broken transaction ratio of 10^{-4} the slope of the number of broken transactions at a speed of 80 km/h is very steep, and a speed increase of 10 km/h will lead to more than a magnitude more broken transactions. Therefore the critical transaction length limit to classify a transaction as broken for a certain vehicle speed was set 20 % below the passage time of the communication zone. Otherwise small changes in the simulator setup could have caused too optimistic values.

The critical case happens when several CEN DSRC OBUs are entering the tolling zone simultaneously. For two simultaneously arriving passenger cars the relation of broken transactions to the total number of transactions for a driving speed of 100 km/h should be less than 10^{-4}. For trucks, the requirement can be relaxed to a driving speed of 80 km/h.

Simulations for passenger cars and for trucks with a single CEN DSRC OBU, two simultaneous entering OBUs, and three simultaneous entering OBUs were performed. The number of broken transactions as function of speed and ITS-G5 idle time T_{off} and transmission time T_{on} was evaluated.

5.4.4.2 Interference to one OBU

The interference to a CEN DSRC transaction was investigated for a transmission time T_{on} = 1 ms and an idle time range T_{off} from 50 ms to 1 000 ms for the OBU9 transaction.

The results of the simulations are shown in clause C.3.1.1. Compared to the results with simultaneous CEN DSRC transactions, the same T_{off} time results in less broken transactions and the T_{off} limits to ensure a certain transaction failure rate are less dependent on the number of interferers. Therefore the properties of the interference to a single CEN DSRC transaction were not used to recommend the limits for T_{off} and T_{on}, since simultaneous CEN DSRC transactions are usual and very common in multilane free flow tolling stations.

5.4.4.3 Interference to two simultaneous CEN DSRC transactions

A CEN DSRC tolling station can handle two simultaneous transactions at usual speeds (80 km/h for trucks, 100 km/h for cars) without any significant performance degradation compared to single transactions. The simulation results show that the relative number of broken tolling transactions caused by interference can be limited to 10^{-4} if the number of interferers, the idle time T_{off}, and the transmission time T_{on} are correctly aligned. From the simulation results of the interference to two simultaneous transactions, a method to calculate the necessary T_{off} time as function of the number of interferers *n* (cars) and the transmission time T_{on} was developed (see clause 5.5.2). In the following figures the results of this method are depicted as "Theory".

Clause C.3.1.2 shows the cumulative ratio of potentially broken transaction as function of the vehicle speed for two simultaneous CEN DSRC transactions and for different numbers of interferers *n* (cars). From these results the number of transactions exceeding 80 % of the communication time at 80 km/h (truck OBU) was summarised in figure 22 for different numbers of interferers *n* (cars). The extrapolated T_{off} values at a potentially broken transaction ratio of 10^{-4} were used to determine an appropriate model (see clause 5.5.1).

The dependency of the idle time T_{off} on the ITS-G5 transmission time T_{on} was evaluated for 4, 10 and 20 interferers (cars) for T_{on} vales of 1 ms, 2 ms, 3 ms and 5 ms. Figure 23 shows the results of these simulations for OBU9 in comparison to the theoretical model described in clause 5.5.2. For more than 4 interferers the simplified model fits quite well to the simulation results, as can be seen in figure 23.

Similar evaluations were done for the passenger car OBU10 for a vehicle speed of 100 km/h. The results are summarized in figure 24. For this transaction type the idle time limit to avoid harmful interference is significantly smaller compared to the truck OBU9. But this advantage is nullified, since passenger cars can drive faster than 100 km/h and the probability that more than two are entering the tolling zone simultaneously is much higher than for trucks. Since the interpretation of simulation results get very difficult when different traffic scenarios with multiple driving speeds are taken into account (see clause 5.4.5) OBU10 was not used to evaluate T_{off} limits.

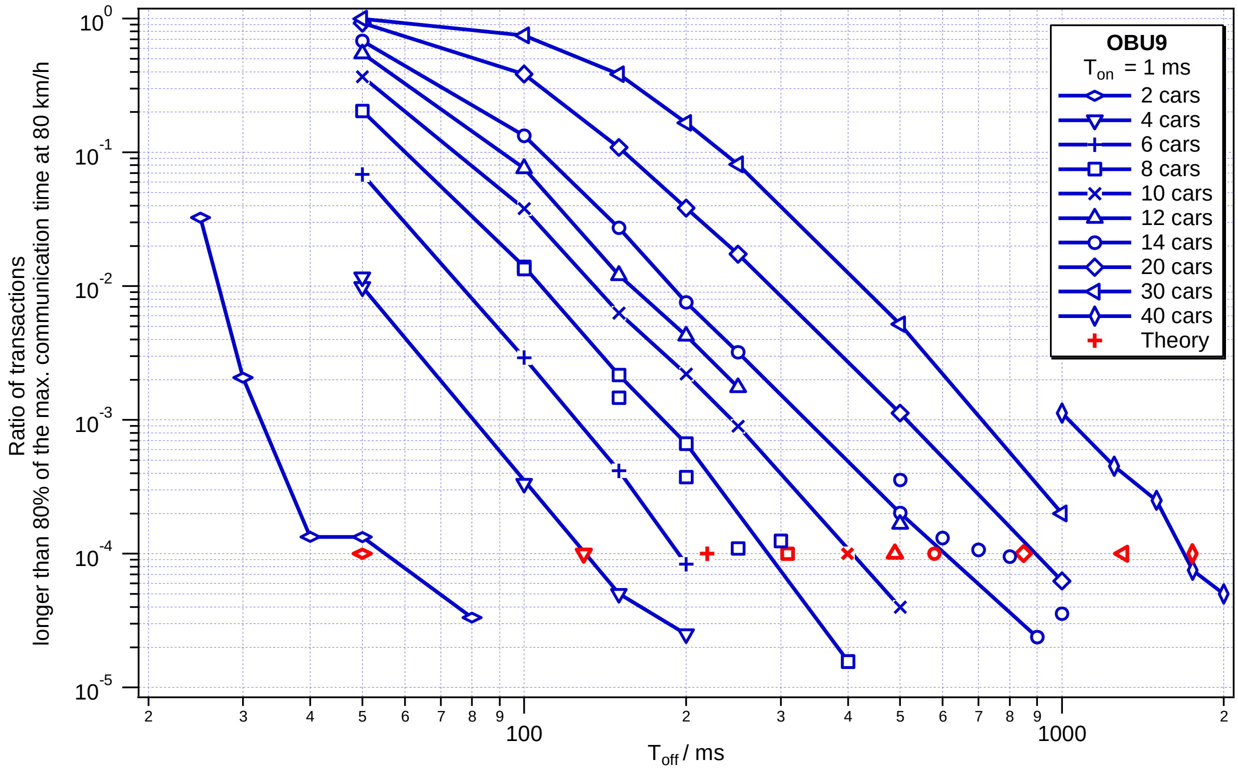


Figure 22: Simulated ratio of potentially broken transactions at a speed of 80 km/h caused by different numbers of interferers (cars) with an activity time T_{on} of 1 ms to two simultaneous CEN DSRC transactions with OBU9

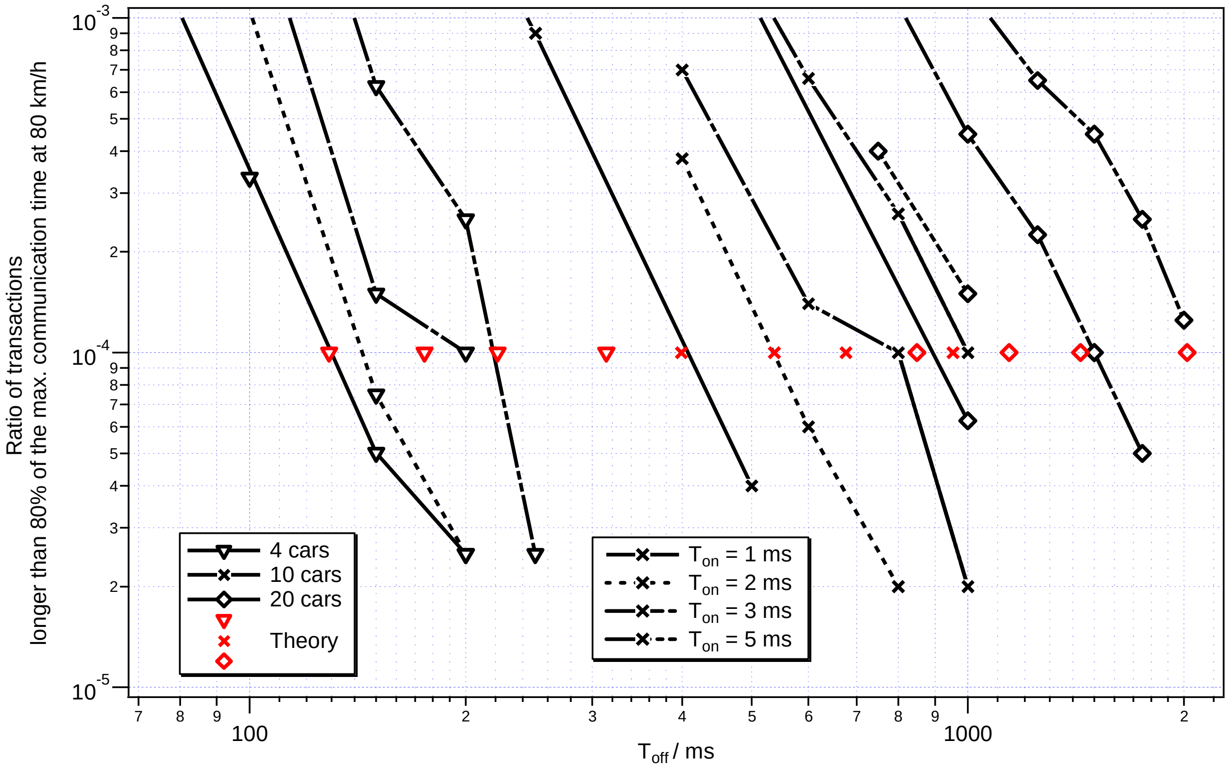


Figure 23: Simulated ratio of potentially broken transactions at a speed of 80 km/h caused by different numbers of interferers (cars) with different activity times T_{on} to two simultaneous CEN DSRC transactions with OBU9

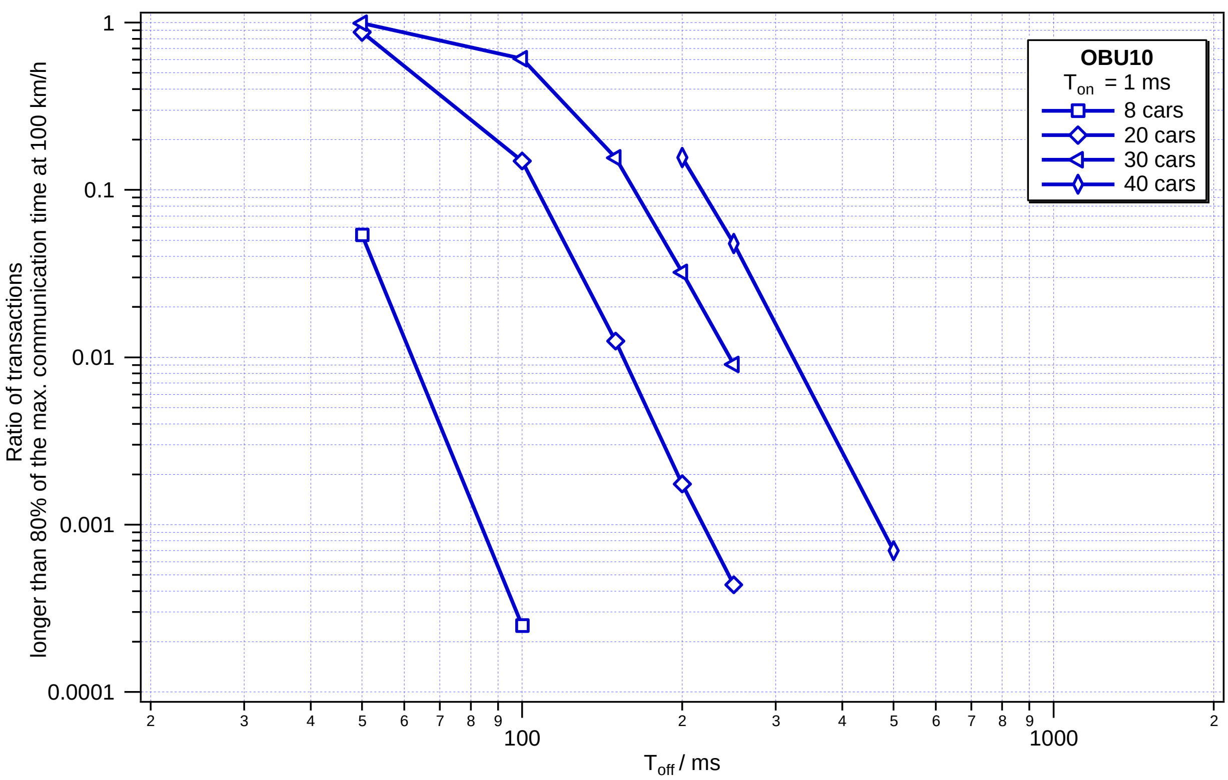


Figure 24: Simulated ratio of potentially broken transactions at a speed of 100 km/h caused by different numbers of interferers (cars) with an activity time T_{on} of 1 ms to two simultaneous CEN DSRC transactions with OBU10

5.4.4.4 Interference to three simultaneous CEN DSRC transactions

Some simulations were also performed for the case of three simultaneous CEN DSRC transactions. While the number of broken transactions without interference is still well below 10^{-4} for a driving speed of 80 km/h, even with only three interferers, a short transmission time T_{on} of 1 ms, and a long idle time T_{off} of 1 s a broken transaction ratio of 10^{-4} cannot be reached. This and some more results are depicted in clause C.3.1.3.

5.4.5 Simulator 2 results: Complex traffic scenarios

5.4.5.1 Fast traffic scenario

Compared to the other mobility simulator setups this scenario with fast and dense traffic (see figure 15 and table 8) did put the highest demands on the tolling system. The simulations were performed with two different passenger car OBUs (OBU12 and OBU10). The results show that OBU12 is not suited for multilane free flow tolling and can be used for toll plazas only, since the broken transaction ratio without interference for this scenario is 3,2 %. For the same setup, the simulation results for OBU10 coincide with the typical broken transaction ratios of operational multilane free flow tolling systems (0,02 %).

To get an upper bound of possible interferes for this scenario, the necessary isolation distances for certain ITS-G5 power levels can be estimated from the CEN DSRC OBU susceptibility limit $P_{itf\,Norm}$ derived from measurements (see table 33) by use of equations B.3 and B.4 in clause B.2 of [i.7]. The path loss coefficient n was set to 1,8, the fading margin σ was set to 6 dB, and the power level at the OBU receiver was set to the $P_{itf\,Norm}$ values of -50,9 dBm for OBU12 and -49,6 dBm for OBU10. No additional antenna or windscreen attenuation correction was necessary since $P_{itf\,Norm}$ already includes these effects. The results are listed in table 10.

Table 10: Upper bound of possible interferes to CEN DSRC for the fast traffic mobility configuration

	OBU12		OBU10	
ITS-G5 TX power level / dBm	Isolation distance / m	Estimated number of interferers	Isolation distance / m	Estimated number of interferers
15	21,5	6	18,2	6
18	31,6	10	26,8	8
24	68,1	26	57,7	24
27	100,0	42	84,7	34
33	215,4	90	182,4	78

Figures 25 and 26 show the broken CEN DSRC tolling transaction ratios that resulted from a simulation of the fast traffic mobility configuration for OBU12 and OBU10. The symbols mark results for different T_{on} times, the bars show the range of two standard deviations obtained from all simulation runs. In table 10 can be seen that for a ITS-G5 TX power levels of 18 dBm the number of possible interferers is in the range of 10. When comparing this result with figure 22, the T_{off} time should be in the range from 400 ms to 1 000 ms depending on T_{on} to avoid interference to a truck OBU at a speed of 80 km/h. Looking at figures 25 and 26 for the passenger car OBUs, these values can also be applied to avoid harmful interference. For higher output power levels the T_{off} time should be much longer than the 2 000 ms studied in these simulation runs, since the number of possible interferers increases dramatically with the TX power level of the ITS-G5 stations.

In practise, high ITS-G5 output power levels will lead to a high ITS-G5 channel load causing packet collisions and to hidden node interference (see table 11). Therefore transmission range (power level) and idle time T_{off} should be controlled by the decentralized congestion control (DCC) to avoid harmful interference to the ITS-G5 communication (see [i.8]). This ensures also coexistence to CEN DSRC.

Table 11: Number of ITS-G5 stations in communication range and possible number of interfering ITS-G5 stations for the fast traffic mobility configuration

ITS-G5 TX power level / dBm	Number of ITS-G5 stations in communication range (σ = -6 dB)	Number of ITS-G5 stations possibly interfering to each other (σ = 6 dB)
15	158	732
18	230	1 078
24	498	2 324
27	732	3 414
33	1 584	7 358

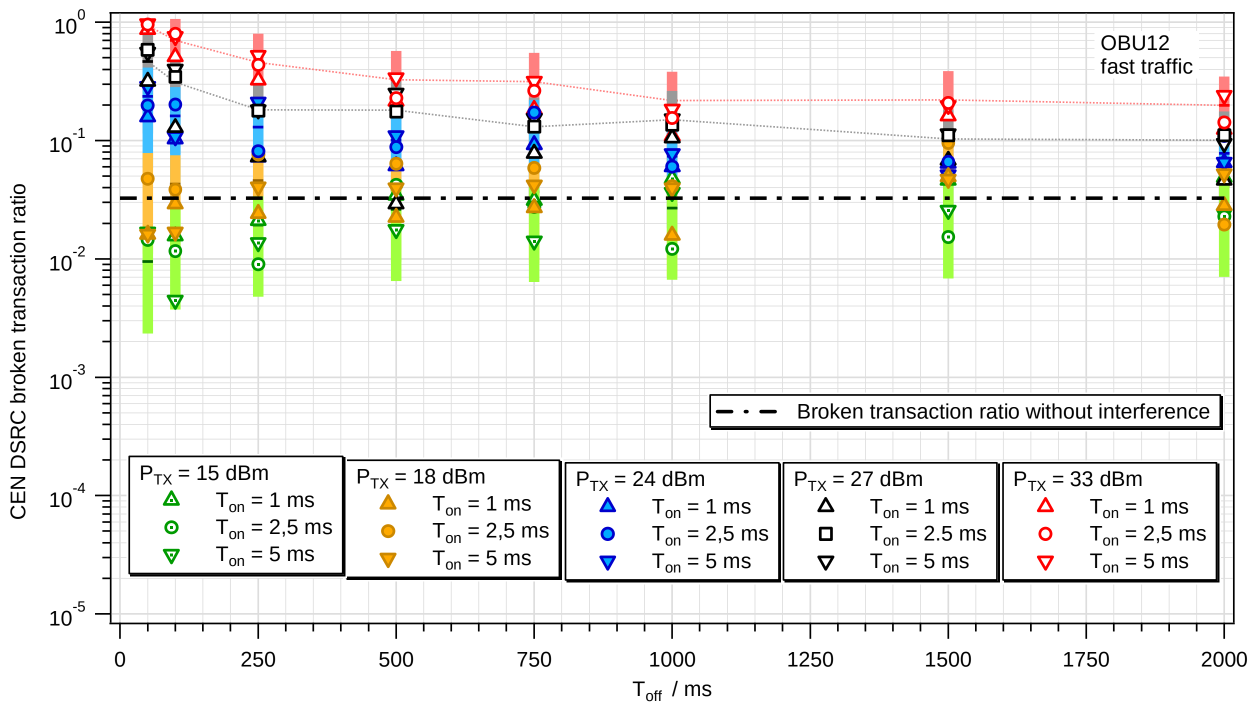


Figure 25: Broken transaction ratio of OBU12 for the fast traffic mobility configuration, different LDC parameters and different ITS-G5 transmit power levels

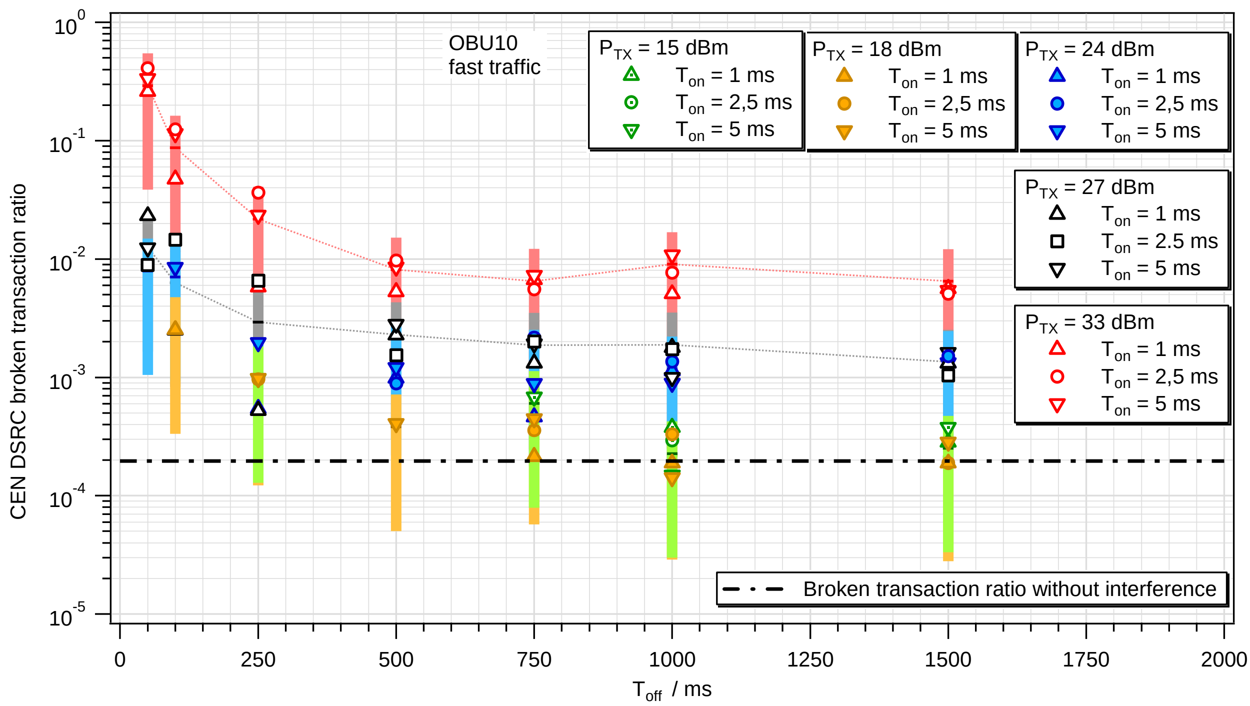


Figure 26: Broken transaction ratio of OBU10 for the fast traffic mobility configuration, different LDC parameters and ITS-G5 transmit power levels

5.4.5.2 Truck scenario

From interference point of view the truck scenario (see figure 18 and table 8) is even more demanding than the fast traffic scenario (see clause 5.4.5.1). Without interference the CEN DSRC tolling system can handle this scenario without a significant number of broken transactions (broken transaction ratio < 10^{-5}). But adding a ITS-G5 station to each vehicle can increase the broken transaction ratio significantly if no appropriate measures are taken (see figures 27 and 28).

To get an upper bound of possible interferes for this scenario, the necessary isolation distances for certain ITS-G5 power levels can be estimated from the CEN DSRC OBU susceptibility limit $P_{itf\ Norm}$ derived from measurements (see table 33) by use of equation B.3 and B.4 in clause B.2 of [i.7]. The path loss coefficient n was set to 1,8, the fading margin σ was set to 6 dB, and the power level at the OBU receiver was set to the $P_{itf\ Norm}$ values of -51,1 dBm for OBU6 and -52,3 dBm for OBU9. No additional antenna or windscreen attenuation correction was necessary since $P_{itf\ Norm}$ already includes these effects. The results are listed in table 12.

Table 12: Upper bound of possible interferes to CEN DSRC for the truck traffic mobility configuration

	OBU6		OBU9	
ITS-G5 TX power level / dBm	Isolation distance / m	Estimated number of interferers	Isolation distance / m	Estimated number of interferers
15	22,1	16	25,8	16
18	32,4	16	37,8	24
24	69,9	48	81,5	56
27	102,6	72	119,6	80
33	221,0	160	257,7	184

Figures 27 and 28 show the broken CEN DSRC tolling transaction ratios that resulted from a simulation of the truck traffic mobility configuration for OBU6 and OBU9. The symbols mark results for different T_{on} times, the bars show the range of two standard deviations obtained from all simulation runs. At some ITS-G5 TX power levels the broken transaction ratio was below 10^{-5} and therefore now result is shown in the graph. In table 12 can be seen, that for a ITS-G5 TX power levels of 18 dBm the number of possible interferers is in the range of 16. When comparing this result with figure 23, the T_{off} time should be around 1 000 ms depending on T_{on} to avoid interference to a truck OBU at a speed of 80 km/h. Looking at figures 27 and 28 for the truck scenario, these values can also be applied to avoid harmful interference for this scenario. Since the simulation takes the realistic antenna pattern of the CEN DSRC OBU into account, the simple omnidirectional assumption overestimates the number of interferers.

In practise, high ITS-G5 output power levels will lead to a high ITS-G5 channel load causing packet collisions and to hidden node interference (see table 13). Therefore transmission range (power level) and idle time T_{off} should be controlled by the decentralized congestion control (DCC) to avoid harmful interference to the ITS-G5 communication (see [i.8]). This ensures also coexistence to CEN DSRC.

Table 13: Number of ITS-G5 stations in communication range and possible number of interfering ITS-G5 stations for the truck traffic mobility configuration

ITS-G5 TX power level / dBm	Number of ITS-G5 stations in communication range (σ = -6 dB)	Number of ITS-G5 stations possibly interfering to each other (σ = 6 dB)
15	264	1 224
18	384	1 800
24	832	3 880
27	1 224	5 696
33	2 640	12 280

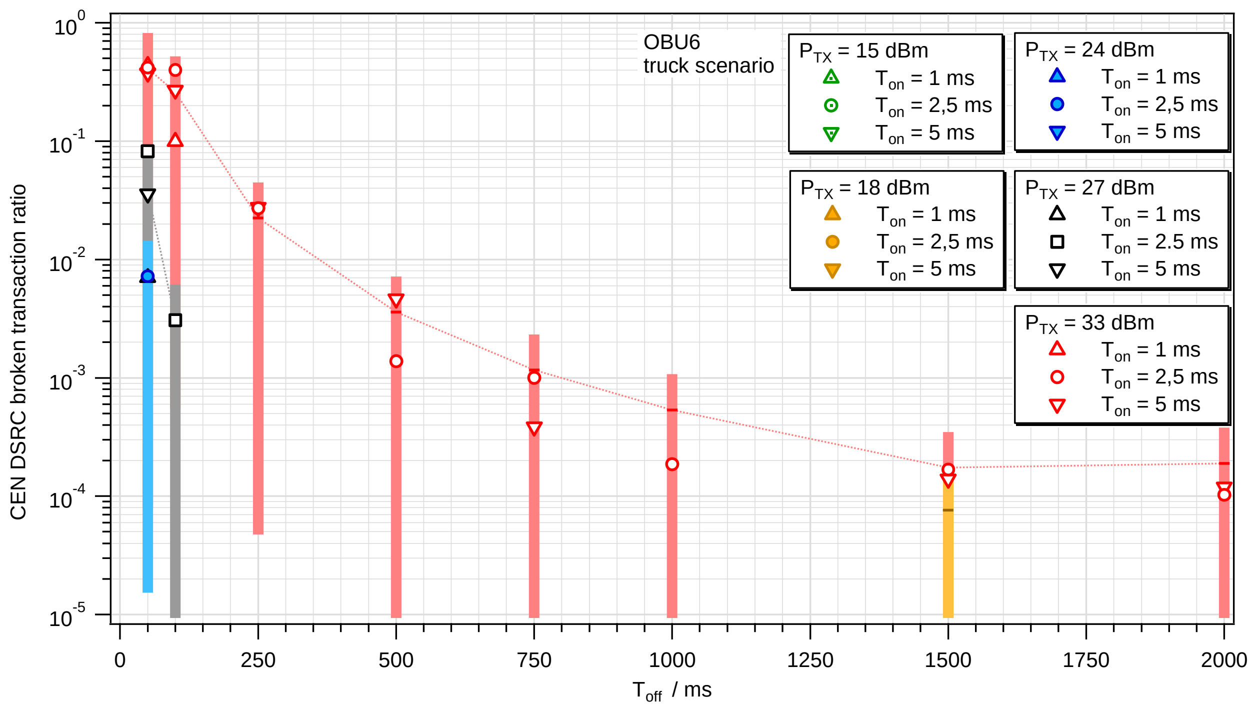


Figure 27: Broken transaction ratio of OBU6 for the truck traffic mobility configuration, different LDC parameters and ITS-G5 transmit power levels

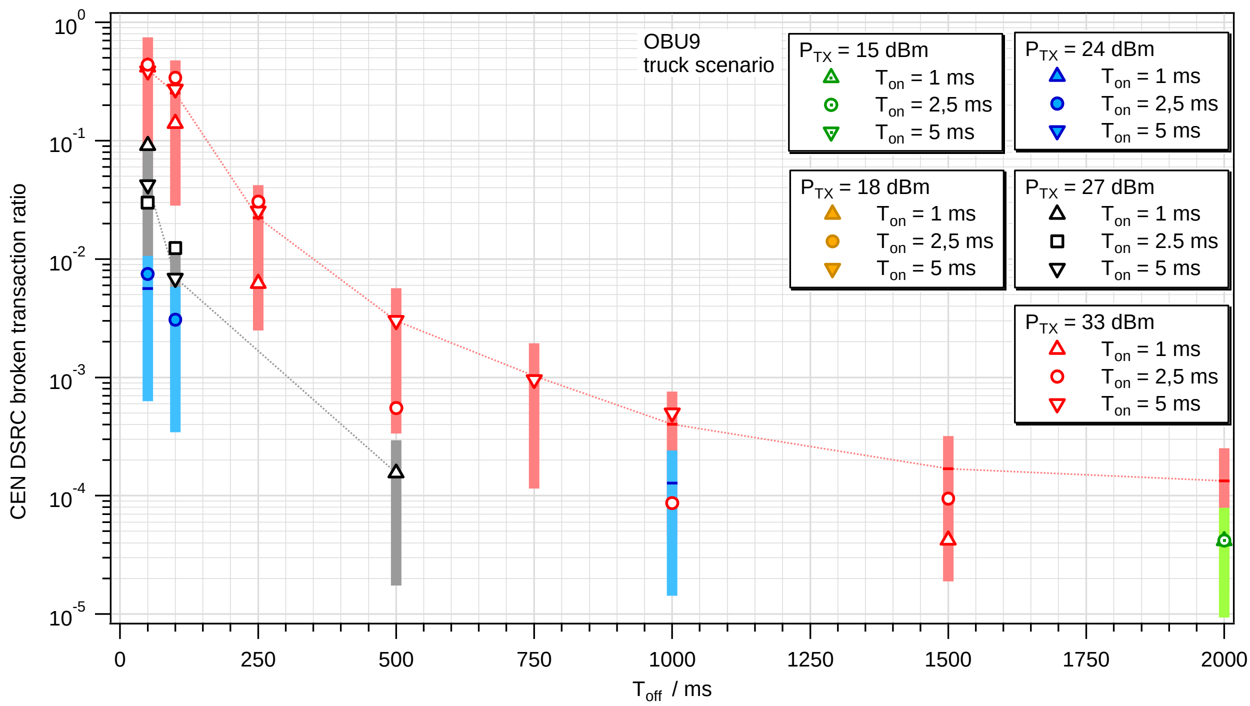


Figure 28: Broken transaction ratio of OBU9 for the truck traffic mobility configuration, different LDC parameters and ITS-G5 transmit power levels

5.4.5.3 Toll Plaza

In the toll plaza setup (see figure 16 and table 8) vehicles are moving slowly, therefore the time to finish a toll transaction is longer than in all other scenarios, but the vehicle and interferer density is much higher. The results show for all OBU types a similar behaviour for an ITS-G5 TX power level of 33 dBm. For lower ITS-G5 TX power levels some OBU types (e.g. OBU6 - figure 29) did not show any interference, while others showed almost the same interference behaviour at 33 dBm and at 15 dBm ITS-G5 TX power level (e.g. OBU10 - figure 31). Since the ITS-G5 MAC reduces the number of concurrent transmissions by delaying packets, the real duty cycle for this scenario with high channel load is altered by the ITS-G5 MAC depending on the number of ITS-G5 stations in range. Since the simulation is also taking the antenna pattern of the CEN DSRC OBU and the interleaved timing of different toll transactions into account, the results show a very complex interference behaviour.

To get an upper bound of possible interferes for this scenario, the necessary isolation distances for certain ITS-G5 power levels can be estimated from the CEN DSRC OBU susceptibility limit $P_{itf\ Norm}$ derived from measurements (see table 33) by use of equation B.3 and B.4 in clause B.2 of [i.7]. The path loss coefficient n was set to 1,8, the fading margin σ was set to 6 dB, and the power level at the OBU receiver was set to the $P_{itf\ Norm}$ values of -51,1 dBm for OBU6, -52,3 dBm for OBU9, -49,6 dBm for OBU10 and -50,9 dBm for OBU12. No additional antenna or windscreen attenuation correction was necessary since $P_{itf\ Norm}$ already includes these effects. The results are listed in table 14.

Table 14: Upper bound of possible interferes to CEN DSRC for the toll plaza configuration

	OBU6		OBU9	
ITS-G5 TX power level / dBm	Isolation distance / m	Estimated number of interferers	Isolation distance / m	Estimated number of interferers
15	22,1	80	25,8	96
18	32,4	128	37,8	144
24	69,9	272	81,5	320
27	102,6	400	119,6	464
33	221,0	880	257,7	1 024
	OBU12		OBU10	
ITS-G5 TX power level / dBm	Isolation distance / m	Estimated number of interferers	Isolation distance / m	Estimated number of interferers
15	21,5	80	18,2	64
18	31,6	112	26,8	96
24	68,1	272	57,7	224
27	100,0	400	84,7	336
33	215,4	848	182,4	720

Figures 29 to 32 show the broken CEN DSRC tolling transaction ratios that resulted from a simulation of the toll plaza configuration for OBU6, OBU9, OBU10 and OBU12. The symbols mark results for different T_{on} times, the bars show the range of two standard deviations obtained from all simulation runs. At some ITS-G5 TX power levels the broken transaction ratio was below 10^{-5} and therefore now result is shown in the graph.

Table 14 shows that for this scenario the number of possible interferers can be very high. But in this scenario high ITS-G5 output power levels would lead to a such a high ITS-G5 channel load that packet collisions and hidden node interference would cause massive packet drops (see table 15). Even the numbers in table 15 are pure hypothetical, in practice there still could be thousands of ITS-G5 stations in range. Therefore transmission range (power level) and idle time T_{off} should be controlled by the decentralized congestion control (DCC) to avoid harmful interference to the ITS-G5 communication (see [i.8]). This will then also ensure coexistence to CEN DSRC.

Table 15: Number of ITS-G5 stations in communication range and possible number of interfering ITS-G5 stations for the toll plaza configuration

ITS-G5 TX power level / dBm	Number of ITS-G5 stations in communication range (σ = -6 dB)	Number of ITS-G5 stations possibly interfering to each other (σ = 6 dB)
15	1 456	6 752
18	2 128	9 904
24	4 592	21 360
27	6 752	31 360
33	14 560	67 568

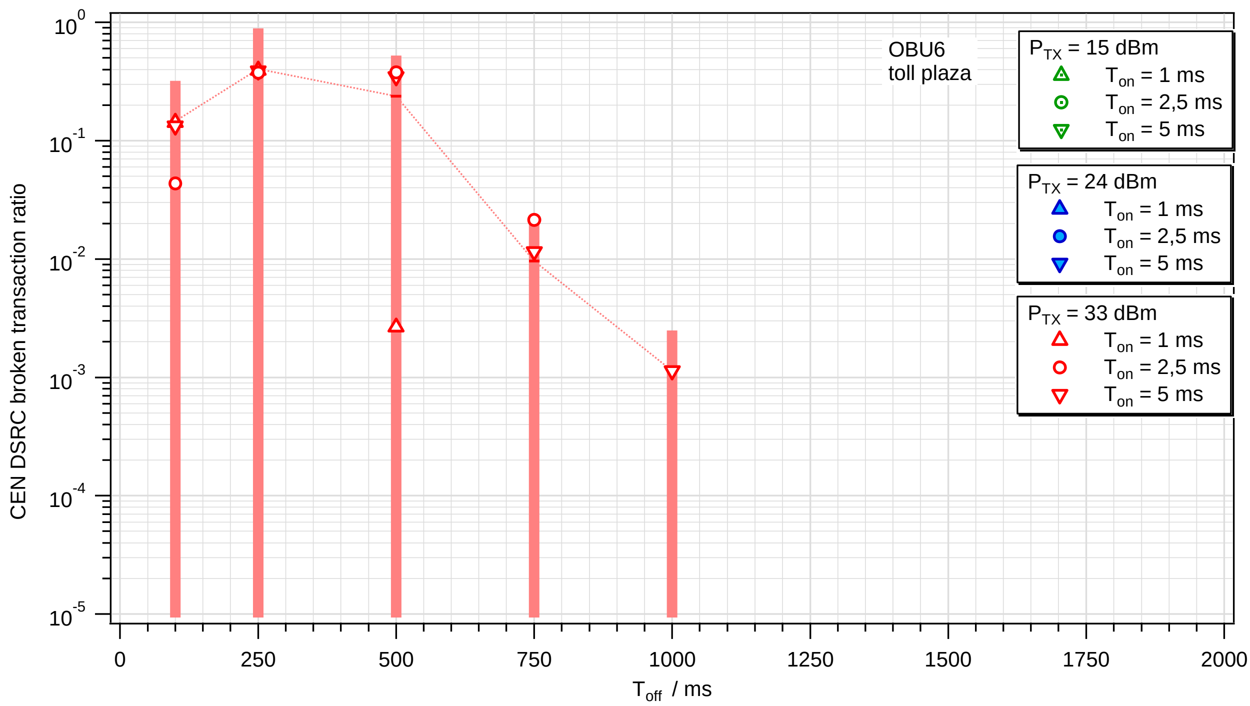


Figure 29: Broken transaction ratio of OBU6 for the toll plaza configuration, different LDC parameters and ITS-G5 transmit power levels

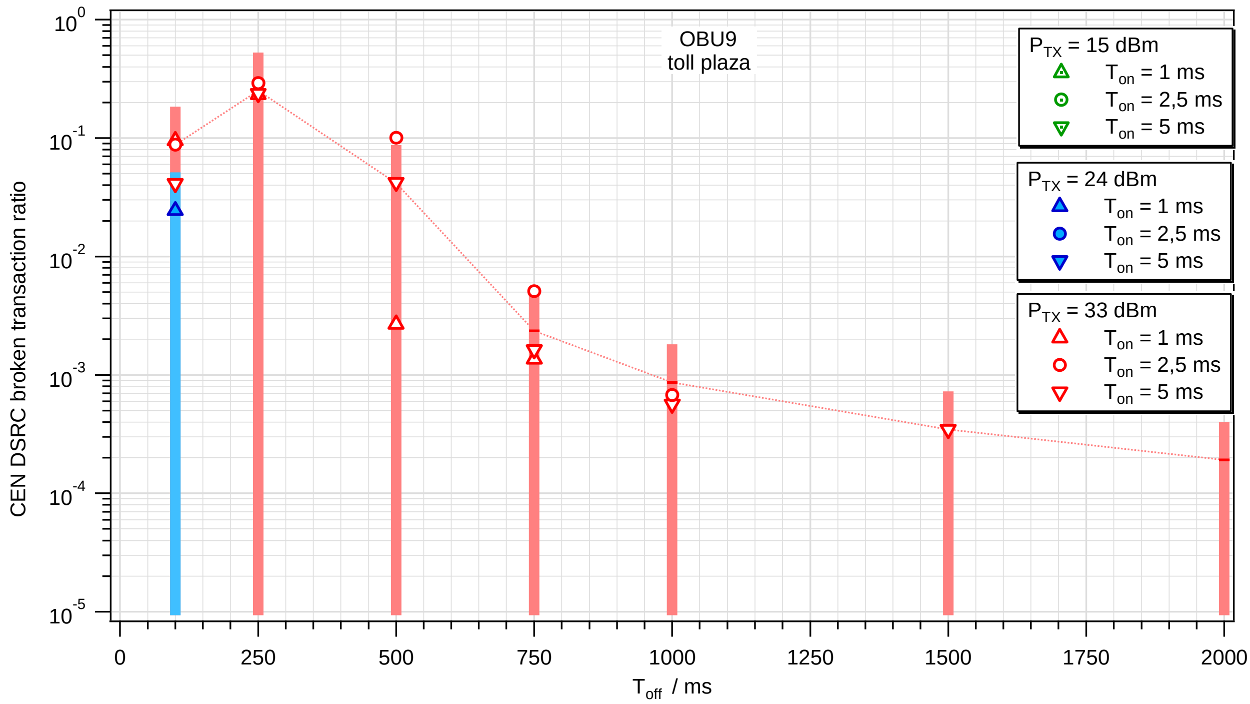


Figure 30: Broken transaction ratio of OBU9 for the toll plaza configuration, different LDC parameters and ITS-G5 transmit power levels

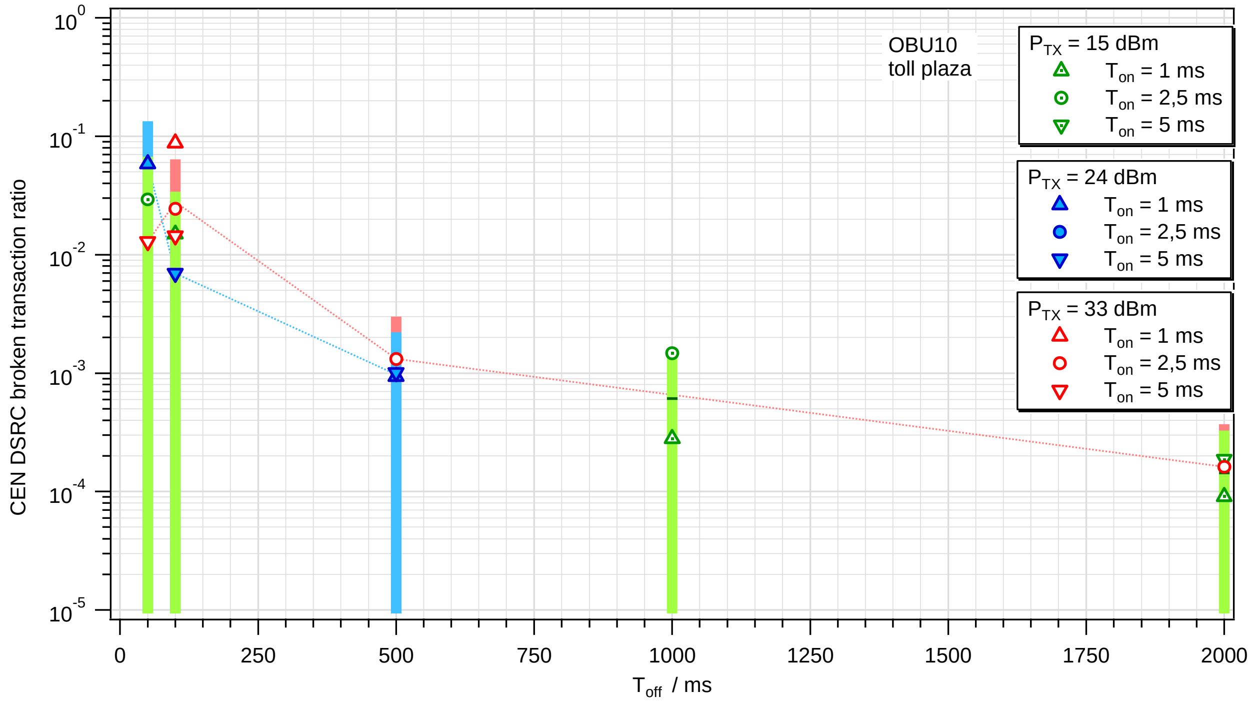


Figure 31: Broken transaction ratio of OBU10 for the toll plaza configuration, different LDC parameters and ITS-G5 transmit power levels

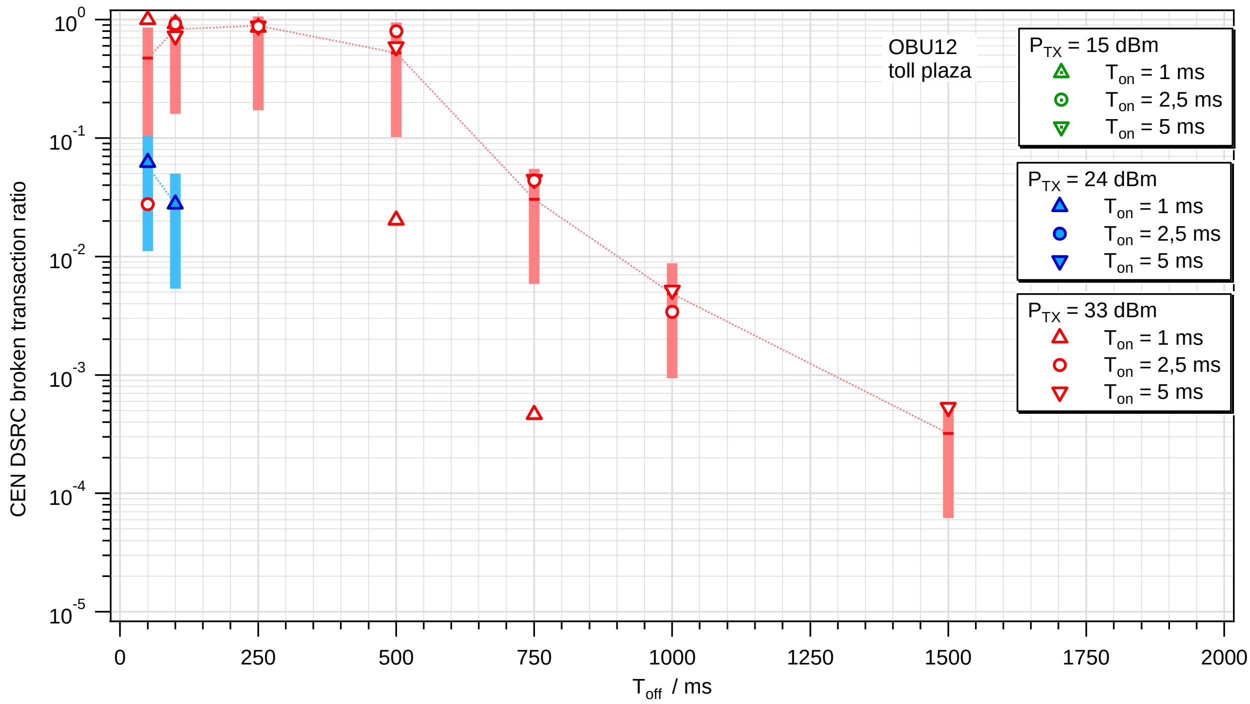


Figure 32: Broken transaction ratio of OBU12 for the toll plaza configuration, different LDC parameters and ITS-G5 transmit power levels

5.4.5.4 Slow traffic

The slow traffic mobility configuration (see figure 14 and table 8) is similar to the toll plaza configuration (see clause 5.4.5.3), but has only 3 lanes for each direction, this reduces the vehicle density and the probability of concurrent toll transactions. Compared to the toll plaza scenario, the impact of ITS-G5 interferers with low TX power levels is reduced for all simulated OBU transaction types.

To get an upper bound of possible interferes for this scenario, the necessary isolation distances for certain ITS-G5 power levels can be estimated from the CEN DSRC OBU susceptibility limit $P_{itf\,Norm}$ derived from measurements (see table 33) by use of equation B.3 and B.4 in clause B.2 of [i.7]. The path loss coefficient n was set to 1,8, the fading margin σ was set to 6 dB, and the power level at the OBU receiver was set to the $P_{itf\,Norm}$ values of -51,1 dBm for OBU6, -52,3 dBm for OBU9, -49,6 dBm for OBU10 and -50,9 dBm for OBU12. No additional antenna or windscreen attenuation correction was necessary since $P_{itf\,Norm}$ already includes these effects. The results are listed in table 16.

Table 16: Upper bound of possible interferes to CEN DSRC for the slow traffic mobility configuration

	OBU6		OBU9	
ITS-G5 TX power level / dBm	**Isolation distance / m**	**Estimated number of interferers**	**Isolation distance / m**	**Estimated number of interferers**
15	22,1	40	25,8	48
18	32,4	56	37,8	64
24	69,9	128	81,5	152
27	102,6	192	119,6	224
33	221,0	416	257,7	480
	OBU12		**OBU10**	
ITS-G5 TX power level / dBm	**Isolation distance / m**	**Estimated number of interferers**	**Isolation distance / m**	**Estimated number of interferers**
15	21,5	40	18,2	32
18	31,6	56	26,8	48
24	68,1	128	57,7	104
27	100,0	184	84,7	152
33	215,4	400	182,4	336

Figures 33 to 36 show the broken CEN DSRC tolling transaction ratios that resulted from a simulation of the slow traffic mobility configuration for OBU6, OBU9, OBU10 and OBU12. The symbols mark results for different T_{on} times, the bars show the range of two standard deviations obtained from all simulation runs. At some ITS-G5 TX power levels the broken transaction ratio was below 10^{-5} and therefore now result is shown in the graph.

Table 16 shows that similar to the scenario in clause 5.4.5.3 the number of possible interferers can get high for high ITS-G5 output power levels. Also in this scenario these high ITS-G5 output power levels would lead to a such an immense ITS-G5 channel load that packet collisions and hidden node interference would cause massive packet drops (see table 17). Even the numbers in table 15 are pure hypothetical, in practice there still could be thousands of ITS-G5 stations in range. Therefore transmission range (power level) and idle time T_{off} should be controlled by the decentralized congestion control (DCC) to avoid harmful interference to the ITS-G5 communication (see [i.8]). This will then also ensure coexistence to CEN DSRC.

Table 17: Number of ITS-G5 stations in communication range and possible number of interfering ITS-G5 stations for the slow traffic mobility configuration

ITS-G5 TX power level / dBm	Number of ITS-G5 stations in communication range (σ = -6 dB)	Number of ITS-G5 stations possibly interfering to each other (σ = 6 dB)
15	510	2 382
18	750	3 498
24	1 620	7 542
27	2 382	11 070
33	5 136	23 850

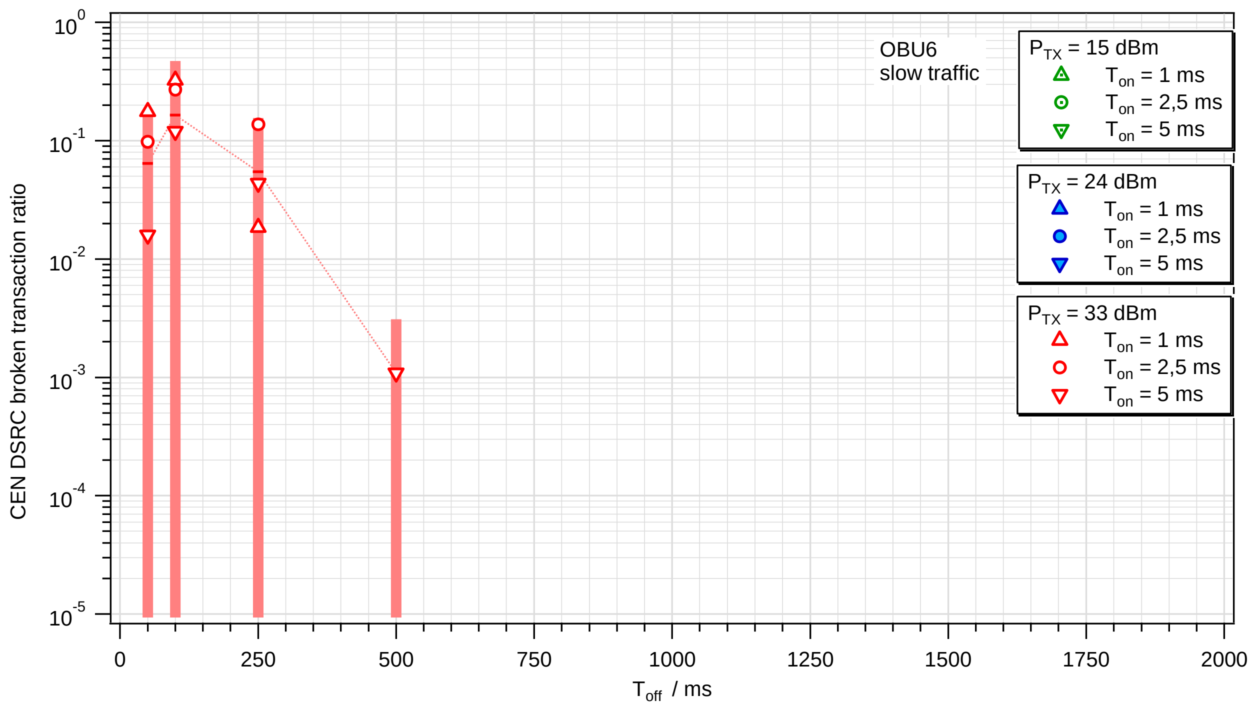


Figure 33: Broken transaction ratio of OBU6 for the slow traffic mobility configuration, different LDC parameters and ITS-G5 transmit power levels

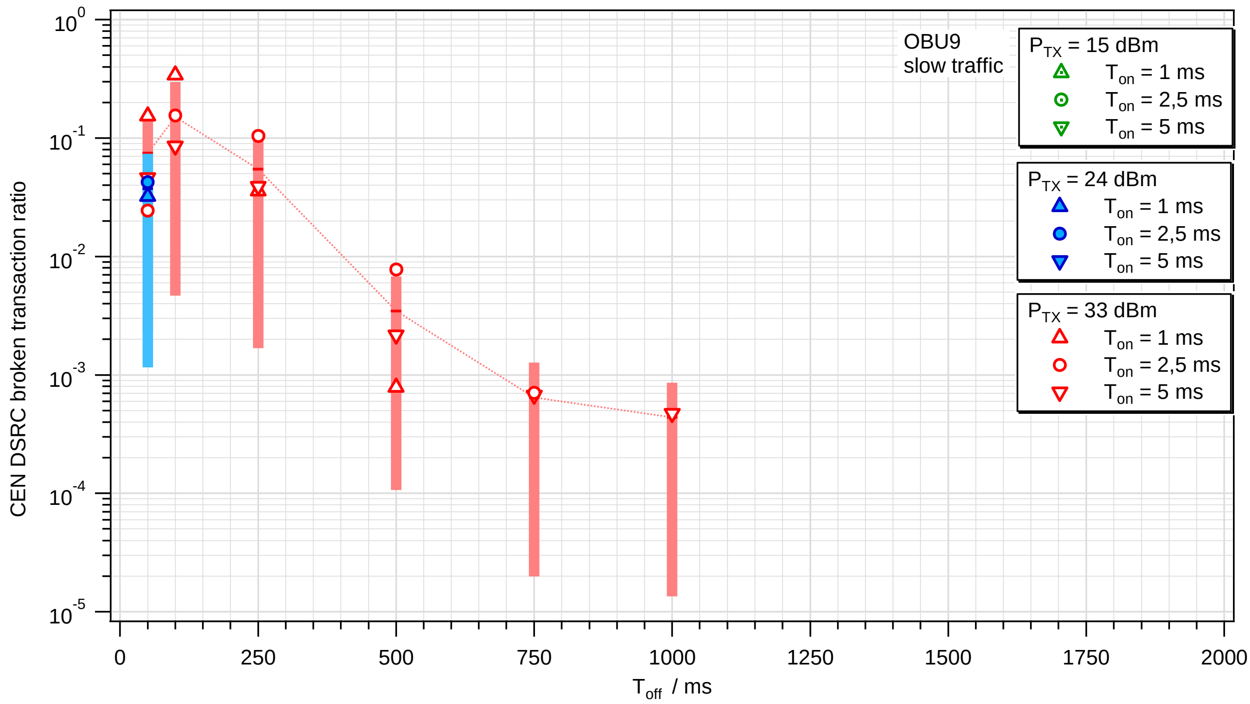


Figure 34: Broken transaction ratio of OBU9 for the slow traffic mobility configuration, different LDC parameters and ITS-G5 transmit power levels

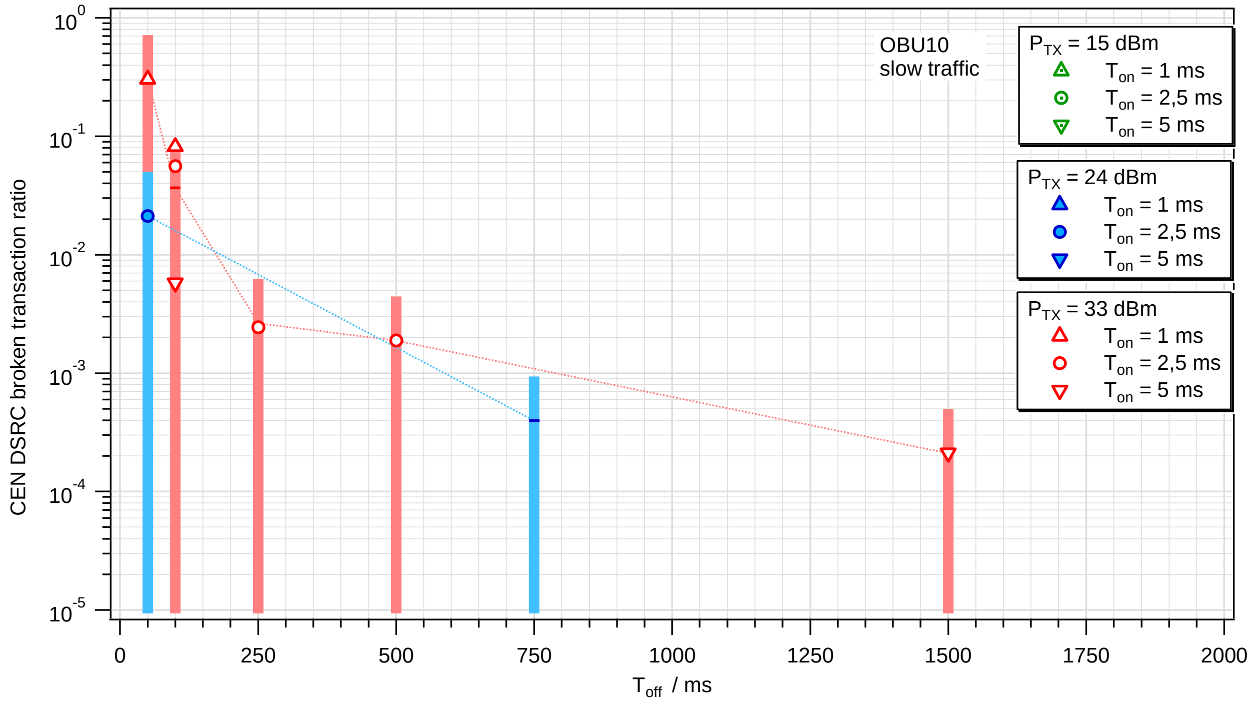


Figure 35: Broken transaction ratio of OBU10 for the slow traffic mobility configuration, different LDC parameters and ITS-G5 transmit power levels

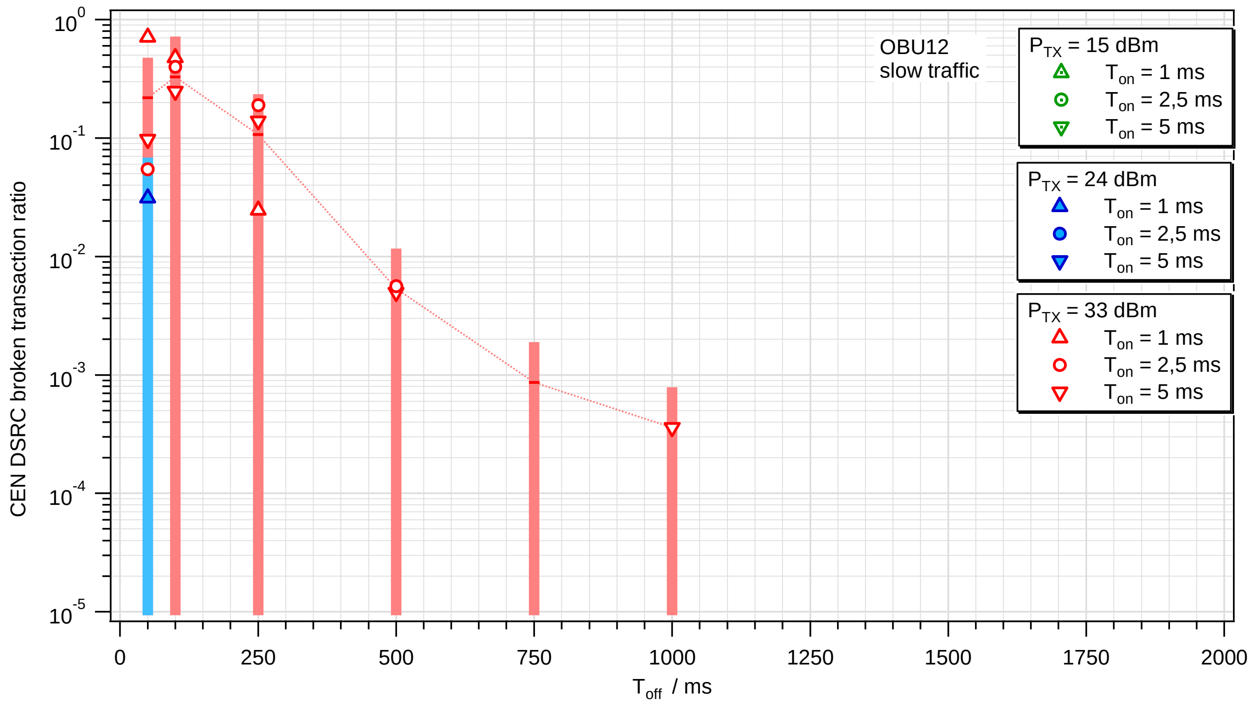


Figure 36: Broken transaction ratio of OBU12 for the slow traffic mobility configuration, different LDC parameters and ITS-G5 transmit power levels

5.4.5.5 Light traffic

The light traffic mobility configuration (see figure 17 and table 8) is a scenario with fast sparsely distributed vehicles. The probability of concurrent toll transactions is low, but also the time while passing the communication zone is low because of the high vehicle speeds.

The upper limit of the broken transaction ratio, evaluated with the passenger car OBU10, was below 10^{-4} for ITS-G5 TX power levels up to 33 dBm and idle times T_{off} down to 100 ms and below 10^{-3} for a T_{off} of 50 ms.

5.5 The T_{off} model

5.5.1 Derivation of the T_{off} model

The purpose of the T_{off} model is to offer a method that calculates the ITS-G5 idle time T_{off}, necessary to avoid harmful interference to CEN DSRC. Simulations and measurements have shown, that this idle time can be derived from the transmission time T_{on} and the number of interferers n.

The model is based on two simultaneous transactions of OBU9, since this scenario suits best as coexistence criteria.

For a fixed transmission time T_{on} the idle time T_{off} can be modelled by a piecewise linear function of the number of interferers n. Figure 37 compares the simulation result for T_{on} = 1 ms with this modelling function.

For a fixed number of interferers and T_{on} within the range from 1 ms to 5 ms the simulation results can be modelled by a linear relation between T_{on} and T_{off}. To simplify the implementation, the T_{off} values are kept constant for T_{on} below 1 ms (see figure 38). Using bursts of ITS-G5 data frames longer than 5 ms is not recommended, since in this case the CEN DSRC performance will degrade rapidly and cannot be modelled by the described simple linear model.

The slope of the relation between T_{on} and T_{off} can be modelled by a simple linear dependency on the number of interferers n (see figure 39).

Figure 40 summarises the dependency of T_{off} on T_{on} and the number of interferers n. The curve for T_{on} = 1 ms (also shown in figure 37) should be used for all ITS-G5 transmission times below or equal 1 ms.

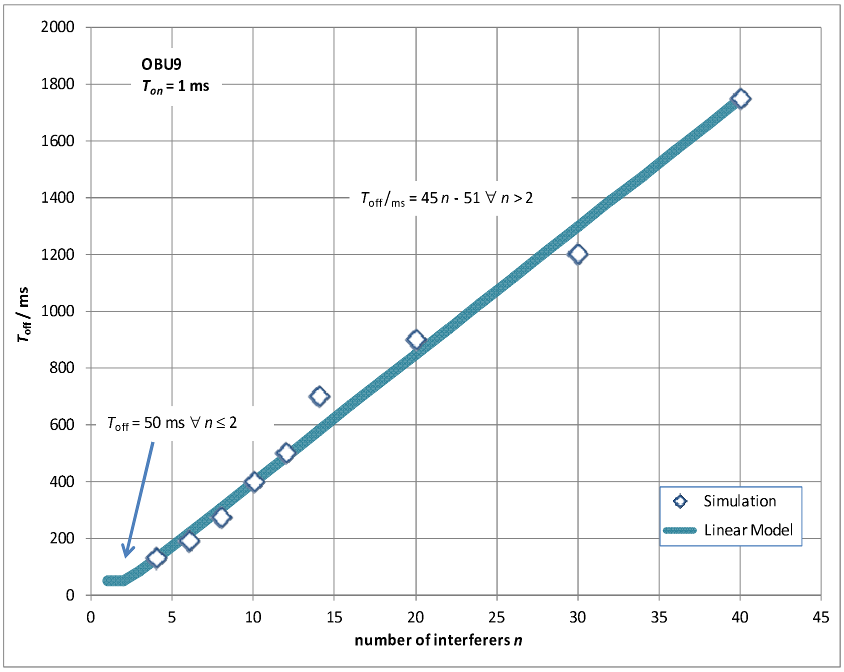


Figure 37: Idle time T_{off} as function of the number of interferers for OBU9 and a transmission time T_{on} of 1 ms

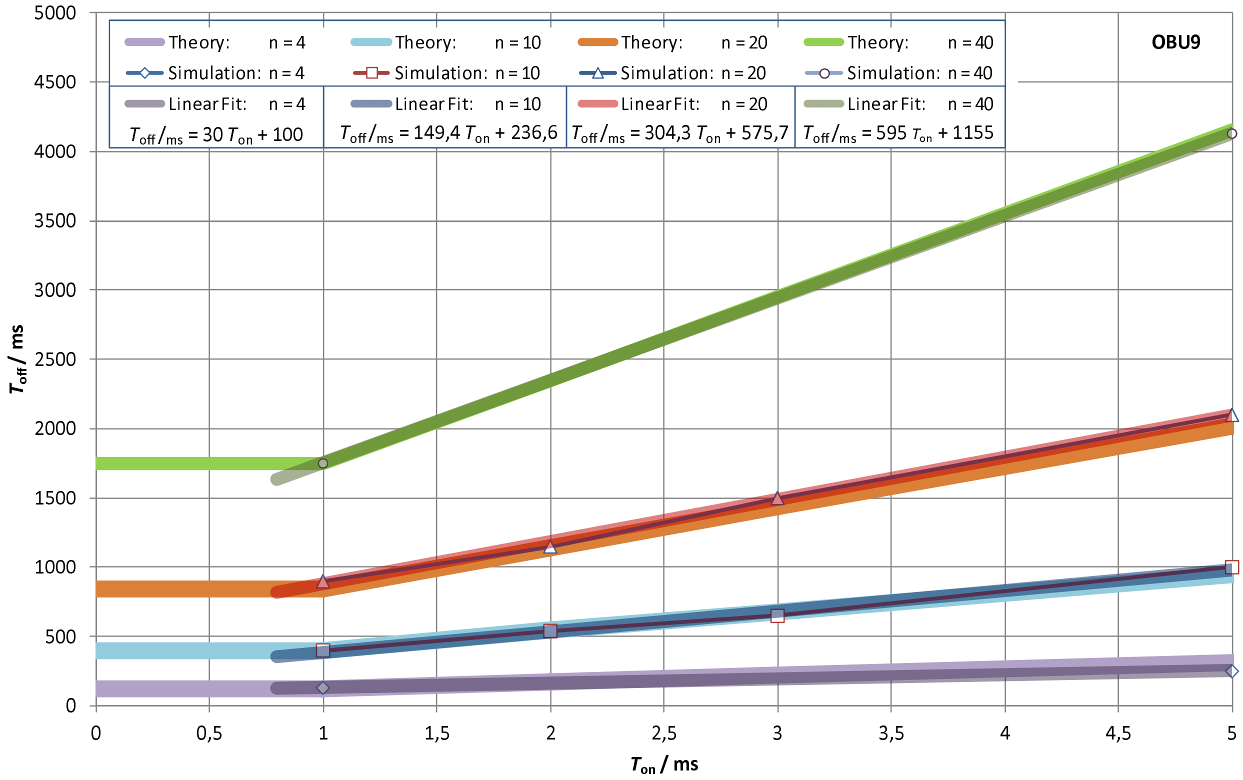


Figure 38: Extrapolated simulation results, linear fits and modelled relation between the transmit time T_{on} and the idle time T_{off}

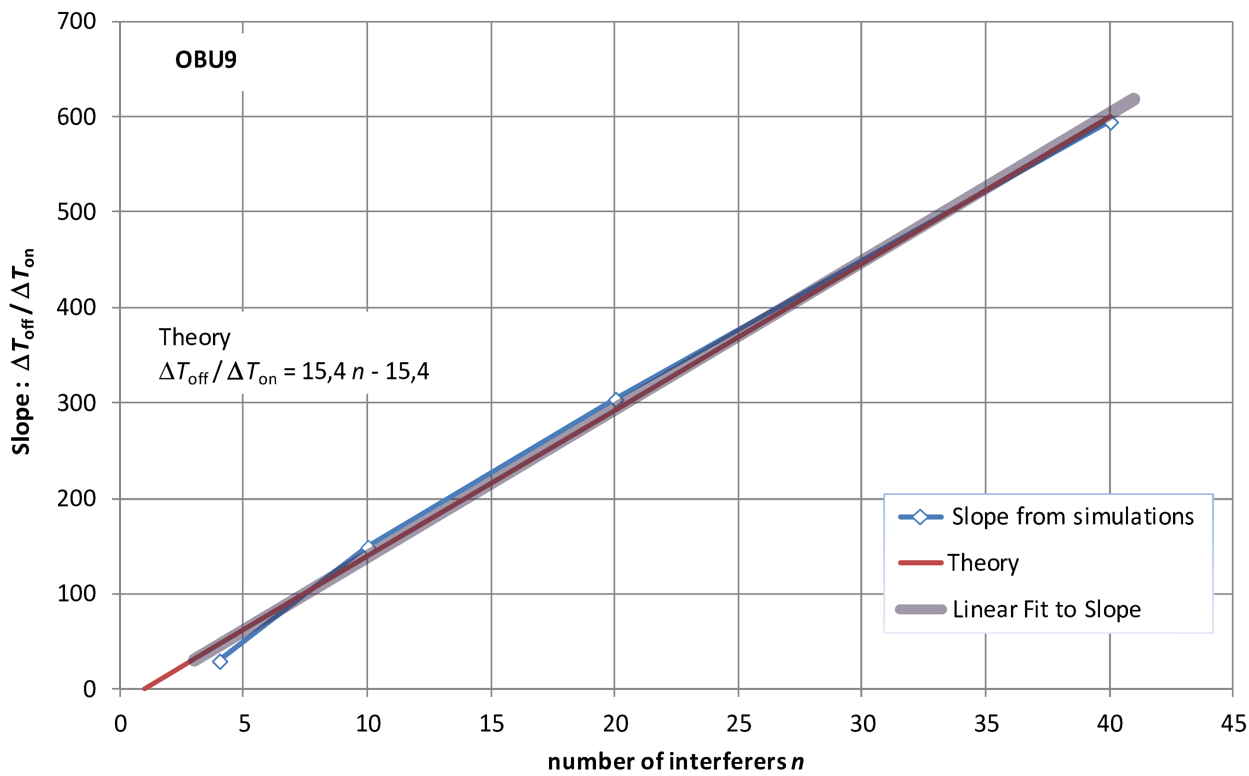


Figure 39: Slope ΔT_{off} / ΔT_{on} for T_{on} values ≥ 1 ms for OBU9 as function of the number of interferers

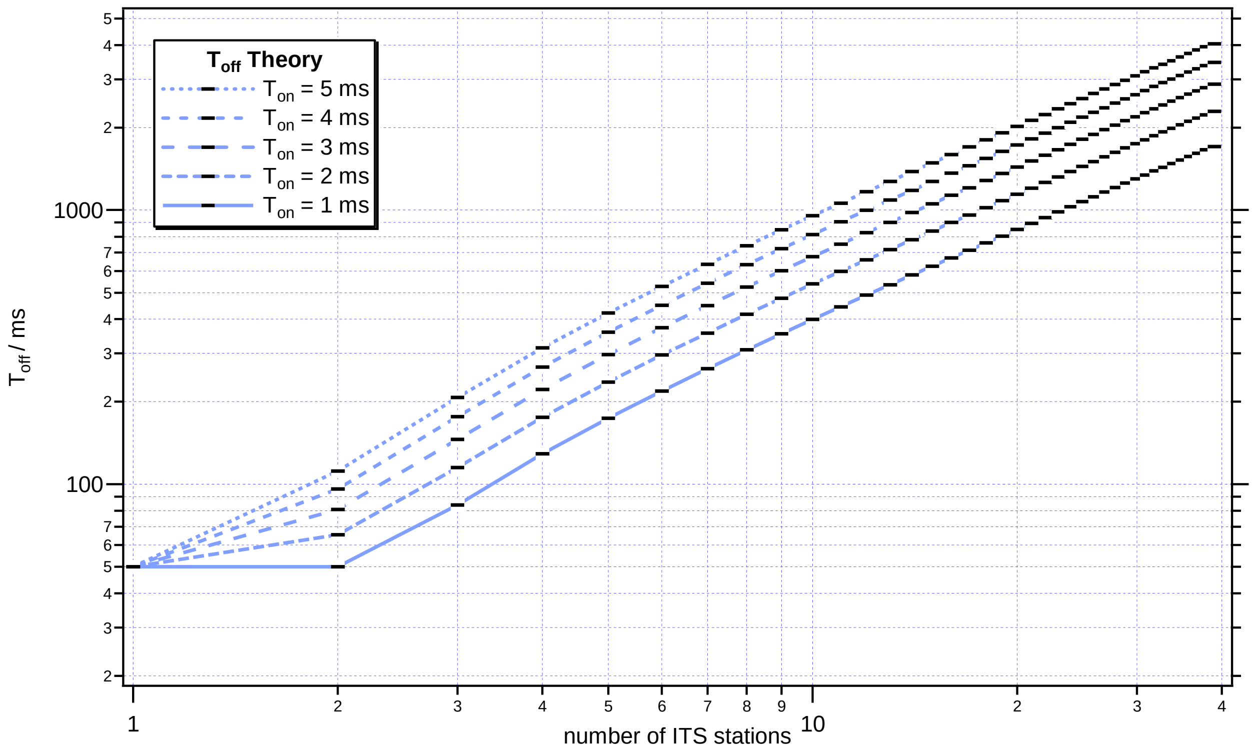


Figure 40: Modelled idle time T_{off} as function of the number of interferers and the transmit time T_{on}

5.5.2 T_{off} model equation

The piecewise linear model for T_{off} is defined by the three model parameters A, B, C, and the two break point parameters BP_{Toff} and BP_{Ton} (see equation 1).

$$T_{off}/ms = \max\{A \cdot n + B \mid BP_{Toff}\} + C \cdot (n-1) \cdot (\max\{T_{on}/ms \mid BP_{Ton}\} - 1) \qquad (1)$$

The parameter values are:

$$A = 45 \qquad (2)$$

$$B = -51 \qquad (3)$$

$$C = 15{,}4 \qquad (4)$$

$$BP_{Toff} = 50 \qquad (5)$$

$$BP_{Ton} = 1 \qquad (6)$$

Where A and B model the relation between T_{off} and the number of interferers n, C adds a dependency on T_{on}, BP_{Toff} (ms) is the lower saturation limit of T_{off}. For T_{on} below the value of BP_{Ton} (ms) the T_{off} value equals the result for $T_{on} = BP_{Ton}$ (ms).

5.5.3 T_{off} model evaluation

To evaluate the model described in clause 5.5.2, Monte Carlo simulations of two simultaneous CEN DSRC transactions with OBU9 and an ITS-G5 timing according to the limits obtained from equation 1 were performed. As evaluation criteria the number of transactions with a length exceeding 80 % of the duration given by the driving speed of 80 km/h and the communication zone length was determined.

Figure 41 shows the evaluation result for T_{on} values of 1 ms and 5 ms. Taking the confidence interval of the simulations into account, the number of reasonably disturbed CEN DSRC transactions does not exceed 0,01 % of the total number of transactions.

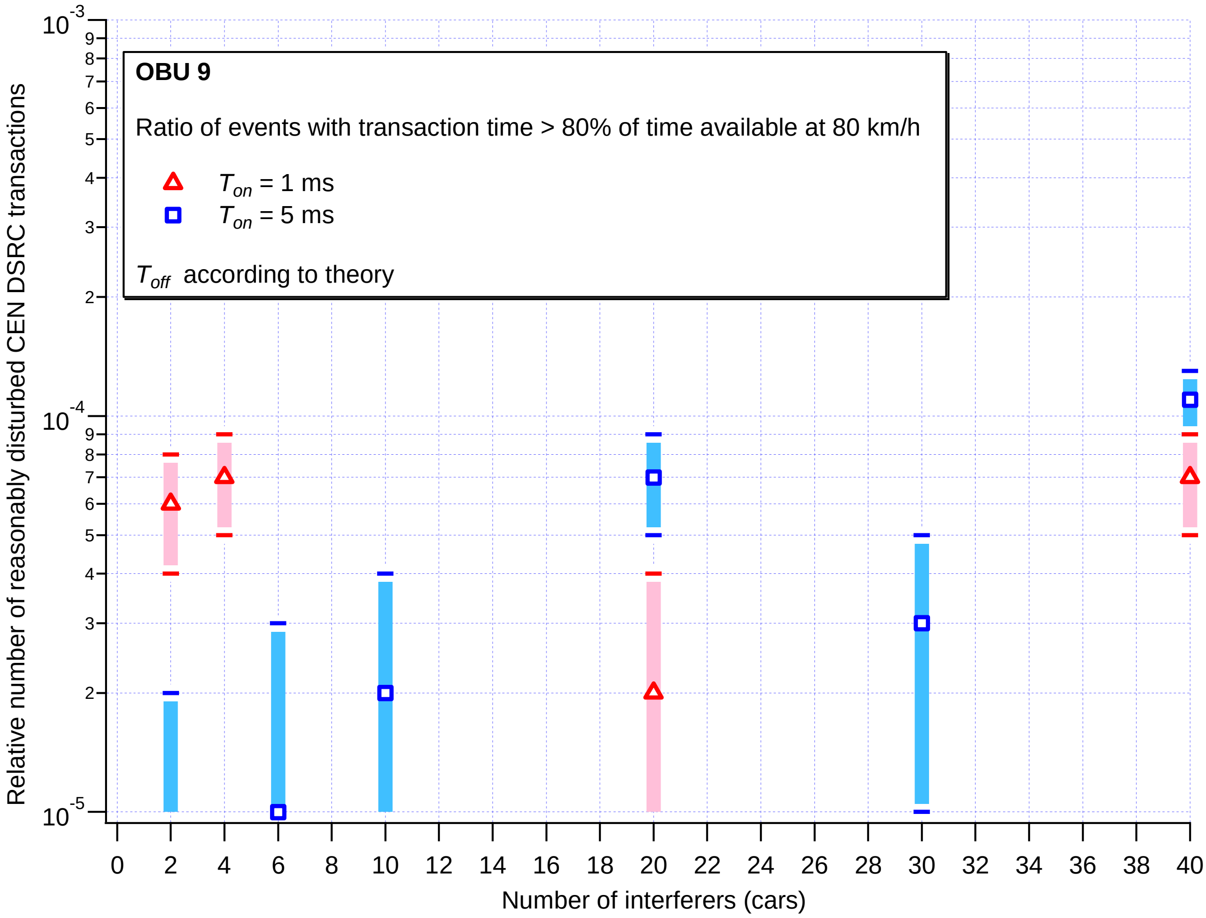


Figure 41: Disturbed transaction ratio of OBU9 for the LDC parameter limits given by the theoretical model

5.6 Conclusion

The initial simulation performed with the CEPT tool SEAMCAT have shown that a coexistence between CEN DSRC and ITS-G5A and G5B can be achieved by proper choice of TX power and the transmission pattern of the ITS system. In order to evaluate these initial results a more detailed simulator has been developed and used. In the second simulation not only statistical results have been used but the full access layer protocol including the timing of both systems have been taken into account.

Simulation 2 shows, that coexistence between CEN DSRC and ITS-G5 devices can be achieved by a combined limitation of ITS-G5 transmit power level and duty cycle. Where the transmit power level reduction is only necessary to decrease the number of potential interferers if the requested transmission bust time T_{on} and the idle time T_{off} are not sufficient to ensure coexistence.

A simple calculation for the determination of the duty cycle parameter limits as function of the number of potential interferes was developed for a typical CEN DSRC transaction. But there can be scenarios (e.g. several CEN DSRC transactions in parallel, high vehicle speeds, etc.) or other transactions (e.g. Swiss border transaction, etc.) that are not totally protected by these limits. The objective was to avoid the most frequent and most probable interference scenarios, so that statistically the interference effect can be neglected.

6 Coexistence Evaluation: Measurements

6.1 Introduction

For the measurements a realistic RSU-OBU system should be set up in the measurement chamber. For that an RSU will be installed in a height of around 5 m and an OBU will be positioned in a distance of around 5 m from the RSU installation foot point. This will lead to a path distance of 7 m between the RSU antenna and the OBU antenna. A typical outline of a measurement chamber is depicted in figure 42. The values and distances are further defined in the configurations below, and will be adjusted according to the needs and real possibilities in the measurement environment. In real installations the height could be up to 6 m for free-flow installations.

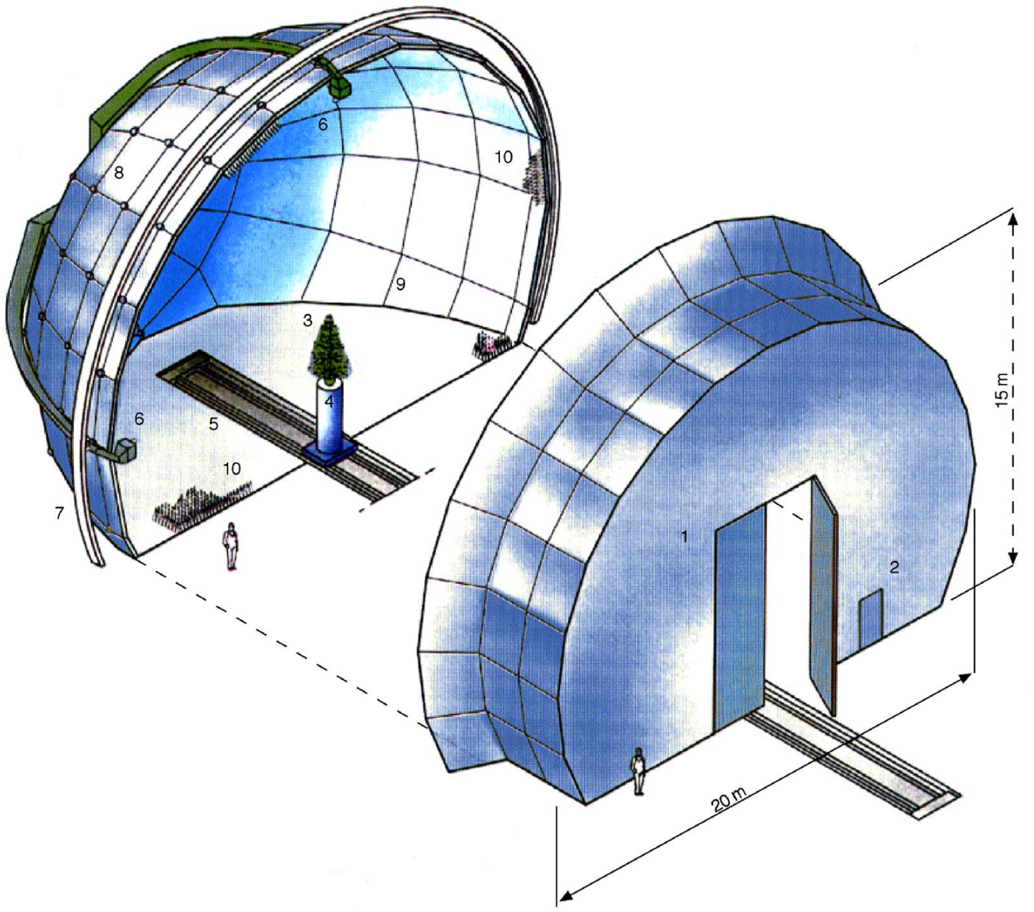


Figure 42: European Microwave Signature Lab (EMSL) at the JRC in Ispra, Italy

6.2 Measurement setup and scenarios

6.2.1 Configurations

In this clause the different used configurations during the Ispra measurements will be presented.

6.2.1.1 Configuration 1; CF#1: Reference measurements

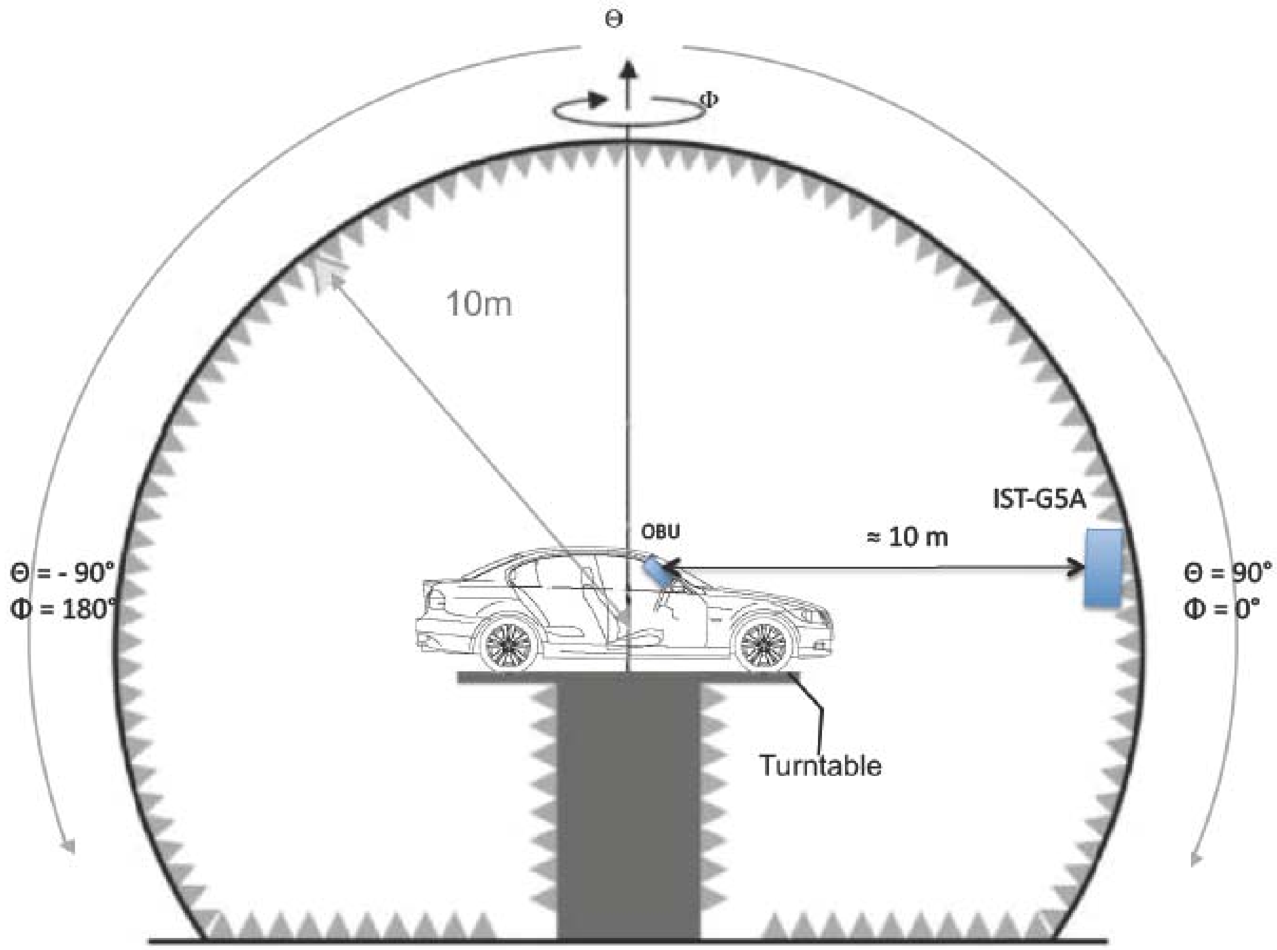


Figure 43: Configuration 1: Reference measurement for interfering ITS signal at receiver antenna (OBU only with antenna and antenna output port)

In figure 43 the configuration 1 is depicted. In this configuration the level of the interfering signal at the CEN DSRC OBU antenna has been evaluated. These measurements have been used as the reference measurements for the ITS power settings and the calibration of the complete signal chain.

In this configuration the CEN DSRC OBU antenna was installed in the car and a spectrum analyser was connected to the OBU antenna output. Then an ITS signal has been injected using the measurement systems antennas. In the configuration no CEN DSRC RSU has been involved.

6.2.1.2 Configuration 2; CF#2: RSU-OBU reference measurements

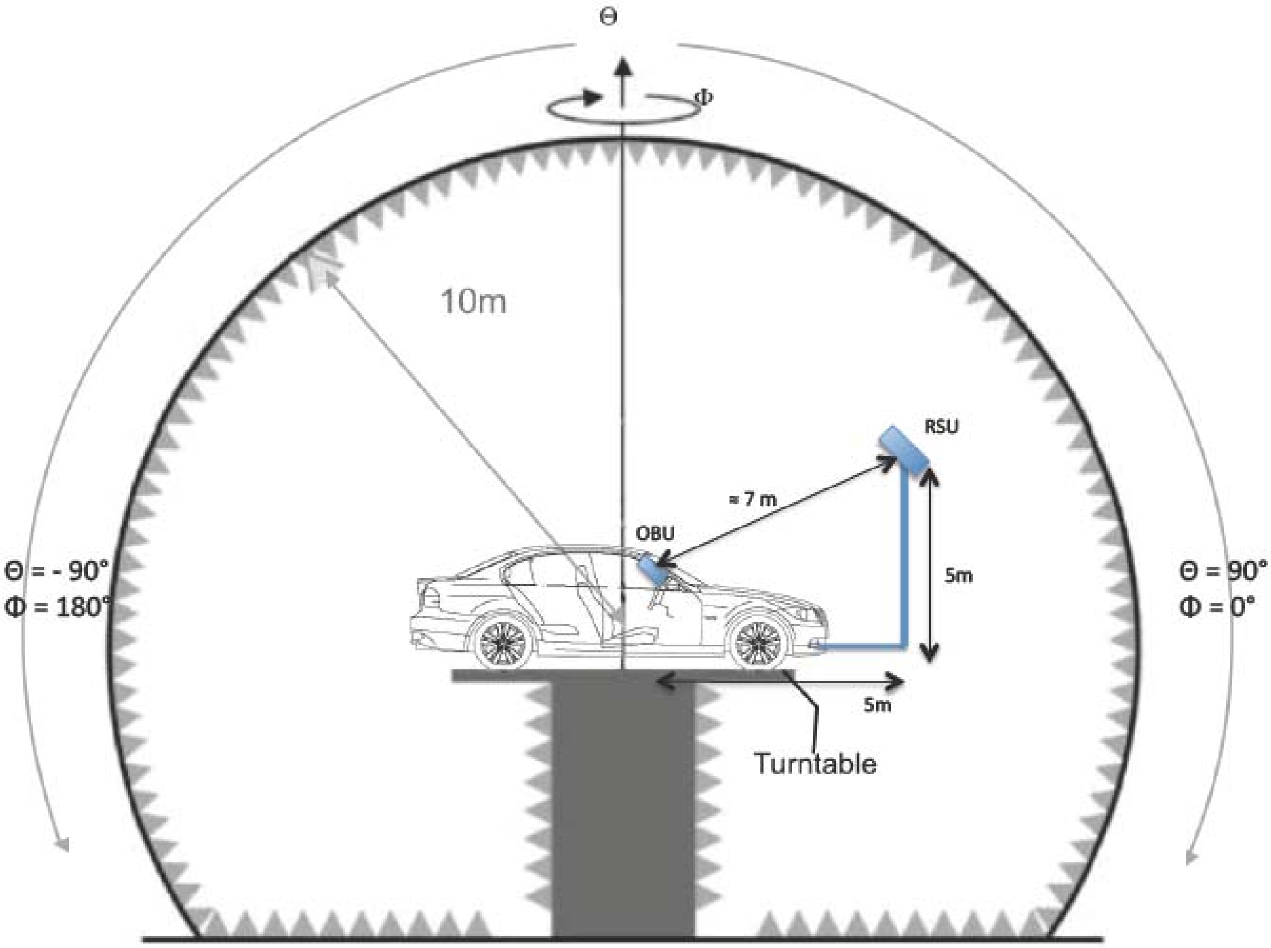


Figure 44: Configuration 2: Reference measurement for CEN DSRC RSU signal

In figure 44 the configuration 2 is depicted. This configuration is used to measure the CEN DSRC signal levels received at the CEN DSRC OBU in the car. The results have been used to set the different operational modes of the CEN DSRC link. In this configuration no ITS interference has been injected.

6.2.1.3 Configuration 3; CF#3: Interference evaluation measurements

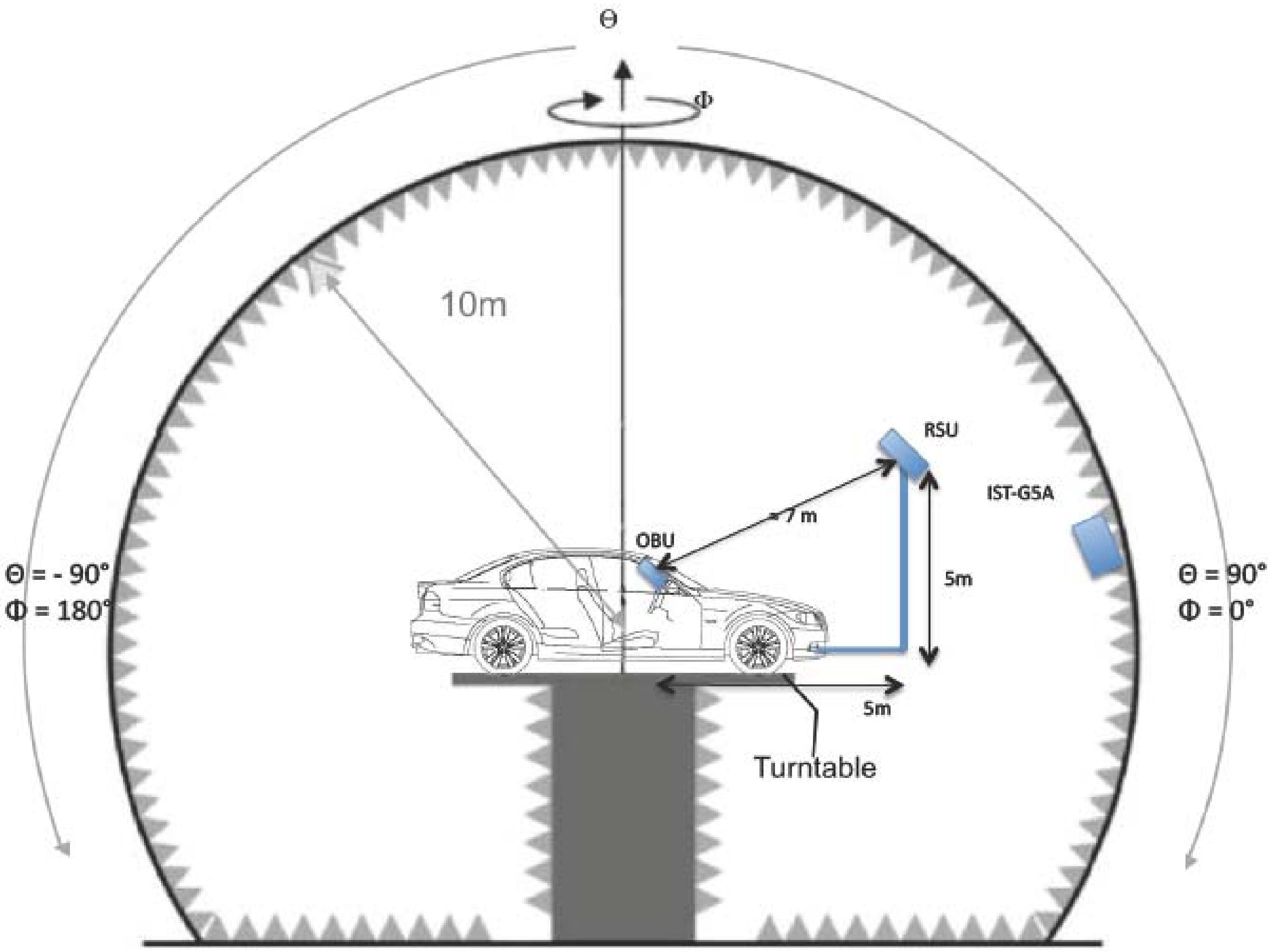


Figure 45: Configuration 3: Setup of CEN DSRC system with RSU and OBU including ITS-G5A interference source

In figure 45 the configuration 3 is depicted. This configuration has been used for the interference evaluation measurements. Here a specific CEN DSRC link mode has been set up and the different kinds of ITS interference have been injected into the OBU installed in the car.

In this configuration both links (CEN DSRC and ITS) are active and thus the effects of the interference into the CEN DSRC systems could be evaluated in the sense of Bit Error Ratio and CEN DSRC Transaction behaviour.

In all configuration presented here only a single interferer has been considered. A specific set up with multiple interferers has been used to demonstrate the multiple interferer case.

6.2.1.4 Car configuration

In addition to the configuration of the measurement chamber, three different car setups were used for several test runs:

- Convertible with open roof (see figure 46)
- Convertible with closed roof - as substitution for a normal passenger car (see figure 47)
- Sports Utility Vehicle (SUV) - as substitution for a truck (see figure 48)

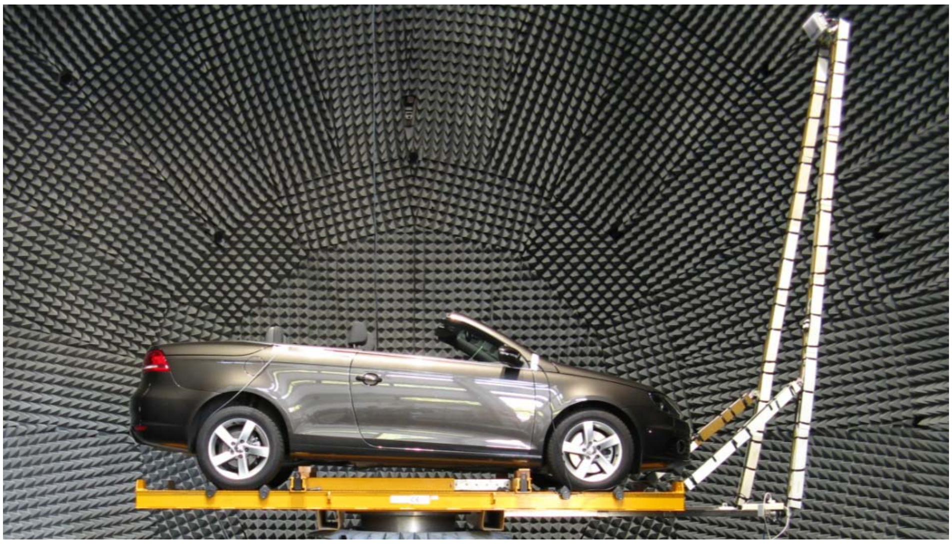


Figure 46: Convertible with open roof

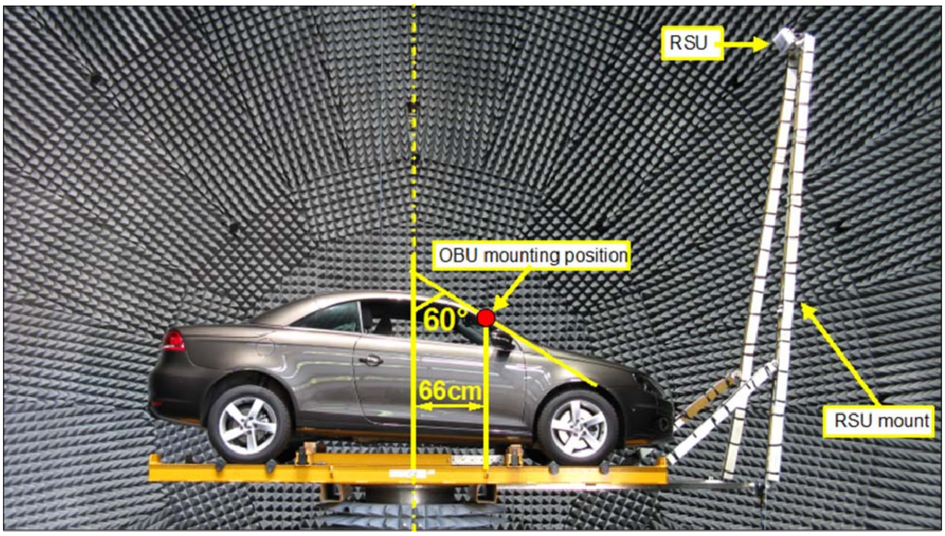


Figure 47: Convertible with closed roof

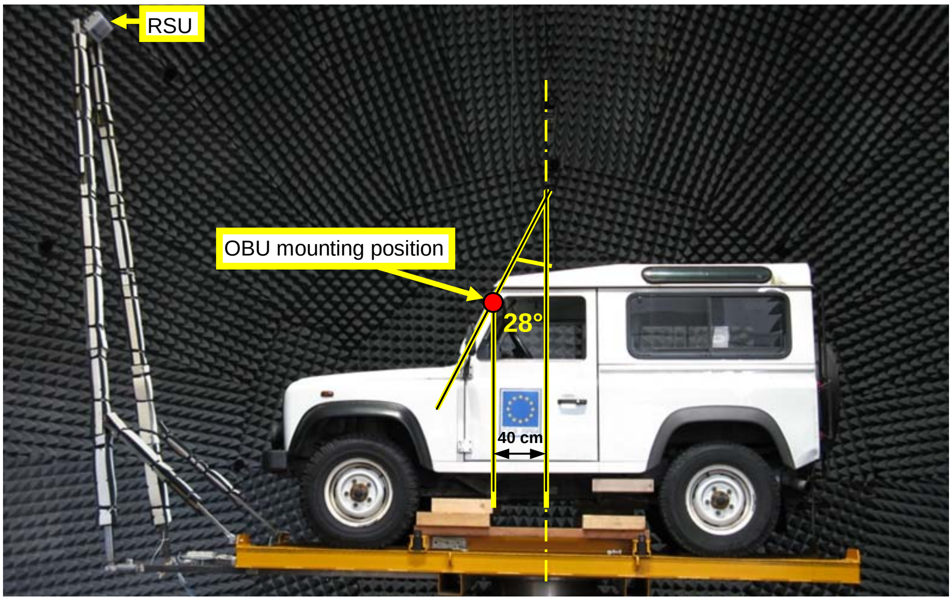


Figure 48: Sports Utility Vehicle

6.2.2 Interference signal generation

The architecture for the interference signal generation is depicted in figure 49. The following equipment is used:

- One low frequency signal generator model AFG3251 from Tektronix, which was used to send an external trigger with a programmable duty cycle to the RF Vector Signal Generator (source of the 802.11p interference signal).
- One RF vector signal generator model E8267D from Agilent Technologies. This instrument was used to generate the 802.11p waveform with the desired parameters. A pc with the Signal Studio software was needed to upload the 802.11p waveforms onto the signal generator internal memory.
- A handheld Spectrum Analyzer model MS2721B from Anritsu, which was used to measure the channel power of the 802.11p interference signal at the OBU inside the vehicle.
- A microwave vector network analyzer model E8358A from Agilent Technologies, which was used for the OBU antenna gain measurements. These tests were conducted without any interference signal present.
- One low frequency signal generator model AFG3251 from Tektronix, which was used to send an external trigger to the vector network analyzer and be able to synchronize the BER measurements with the movement of the sleds and turntable holding the vehicle.

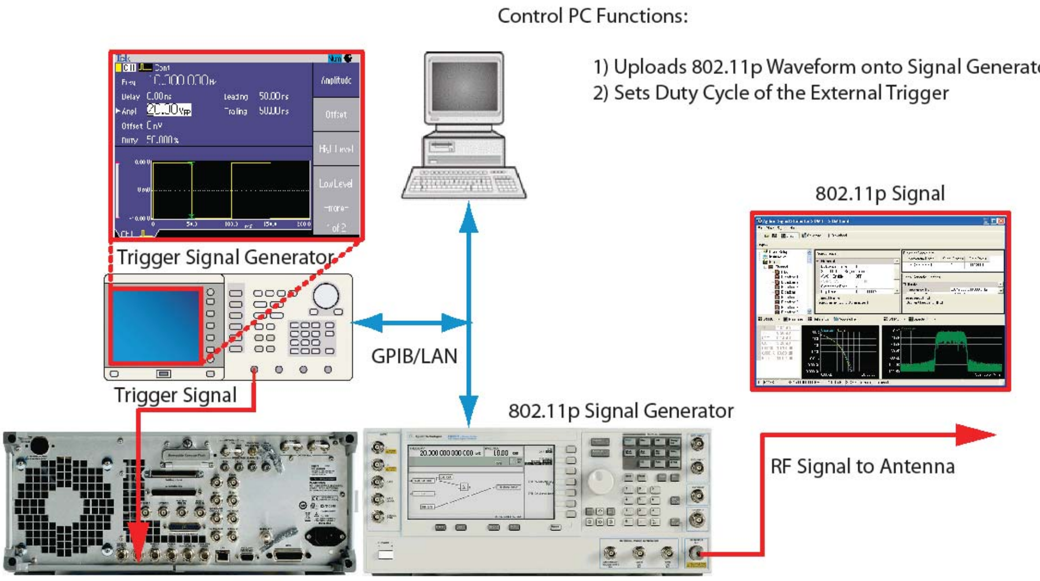


Figure 49: Signal generation chain with programmable signal generator

6.2.3 Reference measurements

The reference measurements are the initial measurements to ensure a proper operation of the system in the different operational stages. The results will be used to interpret the evaluation results in the further steps. Furthermore the results will be used to generate a combined sensitivity pattern of the OBU antenna including the car environmental effects (car attenuations, reflections without passengers).

6.2.3.1 Reference measurement interference signal

In this step the OBU antenna will be replaced by a reference RX antenna at the same position. The reference RX antenna is an OBU system only containing an antenna and an antenna port thus having the same antenna pattern as an original functional OBU. The interferer TX antenna system installed in the measurement hall will be fed with a reference continuous ITS-G5 signal of a specific TX power (39 dBm e.i.r.p.) and a centre frequency of 5,880 GHz. The received interference power will be measured at the position of the OBU at the antenna output port. This test is repeated for each angle from 0 degrees to 360 degrees in 7,5 degree steps (passenger car) or 2,5 degree steps (SUV), respectively.

As a result of this measurement the exact path loss attenuation between the interference TX antenna system and the OBU antenna position can be evaluated. This result will lead to the combined antenna pattern including the car environment (car attenuation, reflections) without the receiver behaviour. The output power at the OBU antenna port (Rx antenna) will be recorded for each antenna position.

Table 18: Definition of TD_CAL_01

Identifier:	TD_CAL_01		
Summary:	Interference signal reference measurement at OBU position		
Configuration:	CF#1		
SUT	ITS-G5A		
Specification Reference:	N/A		
Pre-test conditions:	• ITS unit sends with fixed duty cycle of 100 % • ITS positioned 10 m from OBU at Φ = 0° (in front of OBU) • ITS antenna position in the same height as OBU • OBU replaced by a measurement receiver antenna (OBU only with antenna and antenna output port) • ITS-G5A Channel: SCCH1 (5,875 GHz to 5,885 GHz)		
Test Sequence:	**Step**	**Type**	**Description**
	1	stimulus	ITS unit sends with 39 dBm e.i.r.p.
	2	action	Measure ITS signal strength at OBU position at the antenna output
	3	action	Record spectrum at the ITS TX output
	4	action	Move ITS antenna system as specified in table 19
	5	loop	Repeat step 2 - 4 until final position reached

Table 19: Values for TD_CAL_01

Test TD_CAL_01 shall be executed with the following value combinations		
Sequence Number	**Position**	**Car Type**
Test run 1	Vertical 90 (fixed) Horizontal 0 to 352,5, 7,5 step size	Closed car with glass sun roof
Test run 2	Horizontal 0 (fixed) Vertical 90 to -90, 5,0 step size	Closed car with glass sun roof
Test run 3	Vertical 90 (fixed) Horizontal 0 to 357,5, 2,5 step size	Closed car
Test run 4	Horizontal 0 (fixed) Vertical 90 to -90, 2,5 step size	Closed car
Test run 5	Vertical 90 (fixed) Horizontal 0 to 352,5, 7,5 step size	Open car
Test run 6	Horizontal 0 (fixed) Vertical 90 to -90, 5,0 step size	Open car
NOTE: "Vertical" corresponds to elevation angle and "Horizontal" to azimuth angle.		

6.2.3.2 Reference measurement CEN DSRC tolling system

The different power levels of the CEN DSRC system will be evaluated. In the further interference evaluation measurement steps the CEN DSRC system will be set into two different operational modes:

- **Mode A:** Typical case with a typical path loss attenuation between RSU and OBU and e.g. 6 dB above sensitivity limit.
- **Mode B:** Worst case with a path attenuation leading to an operation of the OBU at the sensitivity limit.

Table 20: Definition of TD_CAL_02

Identifier:	TD_CAL_02		
Summary:	CEN DSRC signal reference measurement at OBU position		
Configuration:	CF#2		
SUT	CEN DSRC RSU		
Specification Reference:	CEN EN 12253 [i.3]		
Pre-test conditions:	• OBU antenna positioned in the middle of the measurement chamber • RSU position around 5 m above reference level and around 5 m away from OBU antenna position		
Test Sequence:	**Step**	**Type**	**Description**
	1	stimulus	RSU unit set to maximum power level (33 dBm e.i.r.p setting)
	2	action	Measure RSU signal strength at OBU antenna position
	3	action	Decrease RSU TX power setting by 1 dB
	4	loop	Repeat step 2 - 3 for OBU antenna output power down to -55 dBm

6.2.3.3 BER reference measurement at the CEN DSRC tolling system with ITS interference

In this reference measurement the dependency of the RSU BER and the ITS interference power will be evaluated using an ITS signal with 100 % duty cycle. The resulting dependency can be used as the reference for further evaluation and as a functional verification of the overall set-up.

Table 21: Definition of TD_CAL_03

Identifier:	TD_CAL_03		
Summary:	CEN DSRC BER reference measurement with ITS interference 100 %		
Configuration:	CF#3		
SUT	CEN DSRC RSU		
Specification Reference:	CEN EN 12253 [i.3], ES 202 663 [i.5]		
Pre-test conditions:	• OBU positioned in the middle of the measurement chamber • RSU position around 5 m above reference level and around 5 m away from OBU position • Set RSU - OBU communication in worst case mode (Mode B) • Set RSU - OBU communication into echo mode • Position ITS interference TX in front of the OBU Φ = 0° and θ = 0° (worst case position for passenger car) • ITS-G5A Channel: SCCH1 (5,875 GHz to 5,885 GHz) • CEN DSRC Channel: highest CEN DSRC channel 5,8125 GHz centre frequency and 5,815 GHz upper channel limit		
Test Sequence:	**Step**	**Type**	**Description**
	1	stimulus	ITS unit sends with 36 dBm e.i.r.p.
	2	action	Measure ITS signal strength at OBU position
	3	action	Record BER of ECHO communication at RSU
	4	action	Decrease ITS TX power by 1 dB
	5	loop	Repeat step 2 - 4 until ITS TX power is < 10 dBm

6.2.4 Measurement 1: OBU Interference sensitivity pattern

Configuration 1 as described in figure 43 applies. The interfering signal will be fed into the chamber's antenna system and transmitted in the direction of the OBU installed in the reference car positioned on the turntable in the middle of the chamber. The chambers antenna system will be moved 180° or 360°, respectively around the OBU installed in the car (Φ in figure 43). At each position the e.i.r.p. power of the interfering signal will be varied from a low level to the maximum level, e.g. 10 dBm to 33 dBm. The interfering signal activity factor in this measurement will be 100 %. The injected interference signal should behave as if it would be at the worst case distance (5 m) to the OBU. Thus the real TX power values of the ITS interfering source need to be increased by 6 dB in order to account for the real distance of 10 m given by the test setup. The tolling station link will be set into two different operational modes:

- **Mode A:** Typical case with a typical path loss attenuation between RSU and OBU and e.g. 6 dB above sensitivity limit.
- **Mode B:** Worst case with a path attenuation leading to an operation of the OBU at the sensitivity limit.

The interfering effect at the CEN DSRC tolling station will be evaluated and recorded.

As a result of this measurement a 360° OBU combined (antenna pattern plus car environment without passenger) interference sensitivity pattern will be generated for the different operational conditions of the RSU - OBU link. This pattern can be used to determine the most critical direction of the interference and also the mitigation factors for interfering sources positioned at different directions around the OBU unit. It can be assumed that the interference sensitivity pattern will be in line with the antenna pattern of the OBU. Figure 50 shows the antenna system that was used for the injection of the ITS-G5 interference signal.

Figure 50: Chamber's movable antenna system

6.2.4.1 OBU sensitivity evaluation measurement

Table 22: Definition of TD_COEX_OBU_01

Identifier:	TD_COEX_OBU_01		
Summary:	OBU Interference sensitivity pattern		
Configuration:	CF#3		
SUT	OBU		
Specification Reference:	CEN EN 12253 [i.3], ES 202 663 [i.5]		
Pre-test conditions:	• ITS unit sends with fixed duty cycle of 100 % • ITS positioned 10 m from OBU at Φ = 0° (in front of OBU) • ITS antenna position at same height as OBU • OBU positioned in the specified car mounting position • RSU positioned based on typical requirements • Stable communication between RSU and OBU in mode A or B respectively • ITS-G5A Channel: SCCH1 (5,875 GHz to 5,885 GHz) • CEN DSRC Channel: highest CEN DSRC channel 5,8125 GHz centre frequency and 5,815 GHz upper channel limit		
Test Sequence:	**Step**	**Type**	**Description**
	1	stimulus	ITS unit sends with initial output power level as shown in table 23 according to the results of TD_CAL_03
	2	action	Record BER of RSU
	3	verify	IF BER < 10^{-6} Goto step 9 ELSE Continue
	4	action	Decrease ITS power by 3 dB
	5	stimulus	ITS unit sends with decreased power
	6	action	Record BER of RSU
	7	verify	IF ITS power < 10 dBm reached or BER < 10^{-6} Non-interference threshold detected, goto step 9 ELSE Continue
	8	loop	Repeat steps 4 - 7
	9	action	Turn ITS clockwise by one angular step as given in table 23
	10	verify	IF all positions covered (Full angular range given in table 23) Goto step 12 ELSE Continue
	11	loop	Repeat steps 1 - 9
	12	action	Stop execution

Table 23: Values for TD_COEX_OBU_01

Test TD_COEX_OBU_01 shall be executed with the following value combinations						
Sequence Number	**Mode**	**Car Type**	**OBU Type**	**ITS-G5 Transmit Power Range e.i.r.p. in dBm**	**Angle step in degrees**	**Angle range in degrees**
Test run 1	Mode A	Closed car with glass sun roof	OBU11	28 to 38	7,5	0 to 180
Test run 2	Mode B	Closed car with glass sun roof	OBU2	19 to 29	15	0 to 180
Test run 3	Mode B	SUV	OBU10	15 to 39	2	0 to 180
Test run 4	Mode B	SUV	OBU12	-5 to 20	2	0 to 180
Test run 5	Mode B	SUV	OBU6	13 to 39	1	-180 to 180
Test run 6	Mode B	SUV	OBU9	9 to 34	2	-180 to 0
NOTE: The ITS-G5 transmit power applied at 10 m distance to the CEN DSRC OBU.						

6.2.5 Measurement 2: Single interferer from front

In this scenario the interfering ITS-G5 station will be positioned directly in front of the OBU unit in a distance of 5 m. This represents the case where a car is directly in front of the victim car equipped with a CEN DSRC OBU. In addition to the normal car case where a passenger car is positioned in front of a passenger car, a scenario using OBUs as victims installed in a truck like position will be measured. In this specific measurement the OBU antenna will have no upwards tilt (see figure 51 a). In the measurement setup the distance will be 10 m and thus a correction factor needs to be taken into account.

In the planned set up the antenna system of the chamber will be used to radiate the ITS-G5 interfering signal. For this measurement the TX antenna will be positioned directly in front of the OBU radiating in the direction of the OBU antenna.

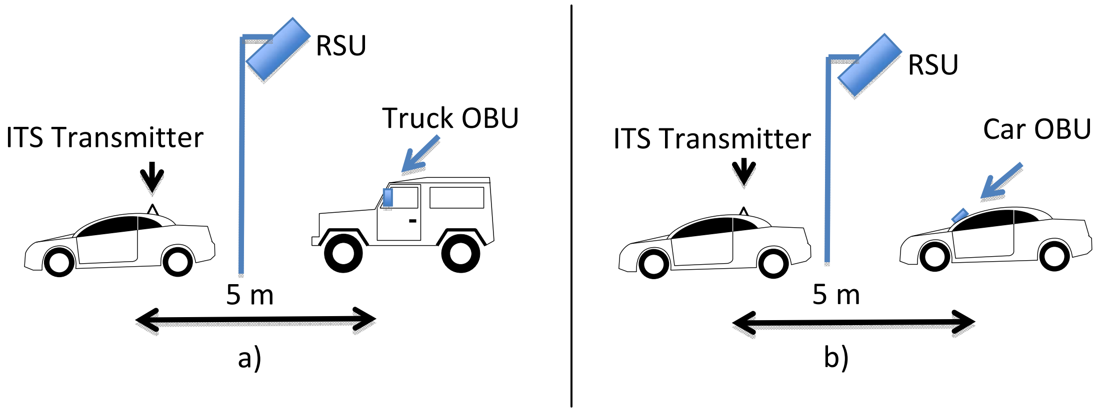


Figure 51: Front interference scenario #CF03, a) Truck b) normal car

6.2.5.1 OBU Interference for different duty cycles, front position

Table 24: Definition of TD_COEX_OBU_02

Identifier:	TD_COEX_OBU_02		
Summary:	OBU Interference for different duty cycles, front position		
Configuration:	CF#3		
SUT	OBU		
Specification Reference:	CEN EN 12253 [i.3], CEN EN 13372 [i.2], CEN EN 15509 [i.6], ES 202 663 [i.5]		
Pre-test conditions:	• ITS unit sends with variable off times (T_{off}) • ITS unit sends with variable packet length • ITS TX power: Level well above recorded interfering level in TD_COEX_OBU_01 (+ 3 dB) • ITS positioned 10 m from OBU at Φ= 0° (in front of OBU) • ITS TX antenna position at same height as OBU • OBU positioned in the middle of the measurement chamber • RSU positioned based on typical requirements • Stable communication between RSU and OBU (bit error rate approximately 10^{-6}) when ITS interference is inactive • ITS-G5A Channel: SCCH1 (5,875 GHz to 5,885 GHz) • CEN DSRC Channel: highest CEN DSRC channel 5,8125 GHz centre frequency and 5,815 GHz upper channel limit		
Test Sequence:	**Step**	**Type**	**Description**
	1	stimulus	ITS unit sends with 29 dBm power value based on initial results with fixed on time and initial off time values as shown in table 25
	2	action	Record number of transactions as shown in table 5 and measure transaction duration and frame re-transmissions per transaction
	3	verify	Determine test verdict based on threshold TER Pass criteria per transaction: Transaction is complete Transaction duration < 100 ms Number of empty uplink frames < threshold value
	4	action	Change to next off time value
	5	loop	Repeat Step 2 to 4 until all off time values done

Table 25: Values for TD_COEX_OBU_02

Test TD_COEX_OBU_02 shall be executed with the following value combinations				
Sequence Number	**OBU Type**	**Car Type**	**T_{On} in µs**	**T_{Off} values in µs**
Test run 1	OBU10	SUV	176	3 000, 6 000, 9 000, 12 000, 15 000, 18 000, 21 000, 24 000, 27 000, 30 000, 33 000
Test run 2	OBU10	SUV	264	3 000, 6 000, 9 000, 12 000, 15 000, 18 000, 21 000, 24 000, 27 000, 30 000, 33 000
Test run 3	OBU10	SUV	1 000	3 000, 6 000, 9 000, 12 000, 15 000, 18 000, 21 001, 24 001, 27 001, 30 001, 33 001, 40 000, 50 000, 60 000, 70 000, 80 000, 90 000, 100 000
Test run 4	OBU10	SUV	3 220	3 000, 6 000, 9 000, 12 000, 15 000, 18 000, 21 000, 24 000, 27 000, 30 000, 33 000, 40 000, 50 000, 60 000, 70 000, 80 000, 90 000, 100 000
Test run 5	OBU10	SUV	5 500	3 000, 6 000, 9 000, 12 000, 15 000, 18 000, 21 000, 24 000, 27 000, 30 000, 33 000
Test run 6	OBU10	SUV	10 000	3 000, 6 000, 9 000, 12 000, 15 000, 18 000, 21 000, 24 000, 27 000, 30 000, 33 000
Test run 7	OBU12	SUV	1 000	3 000, 6 000, 9 000, 12 000, 15 000, 18 000, 21 000, 24 000, 27 000, 30 000, 33 000, 40 000
Test run 8	OBU12	SUV	3 220	3 000, 6 000, 9 000, 12 000, 15 000, 18 000, 21 000, 24 000, 27 000, 30 000, 33 000, 40 000, 50 000, 60 000, 70 000, 80 000, 90 000, 100 000
Test run 9	OBU12	SUV	10 000	3 000, 6 000, 9 000, 12 000, 15 000, 18 000, 21 000, 24 000, 27 000, 30 000, 33 000, 40 000, 50 000, 60 000, 70 000, 80 000, 90 000, 100 000

6.2.6 Measurement 3: Single ITS-G5A Station installed on rooftop

In this measurement the interference effects of an ITS station mounted on the rooftop of a vehicle is evaluated (see figure 52).

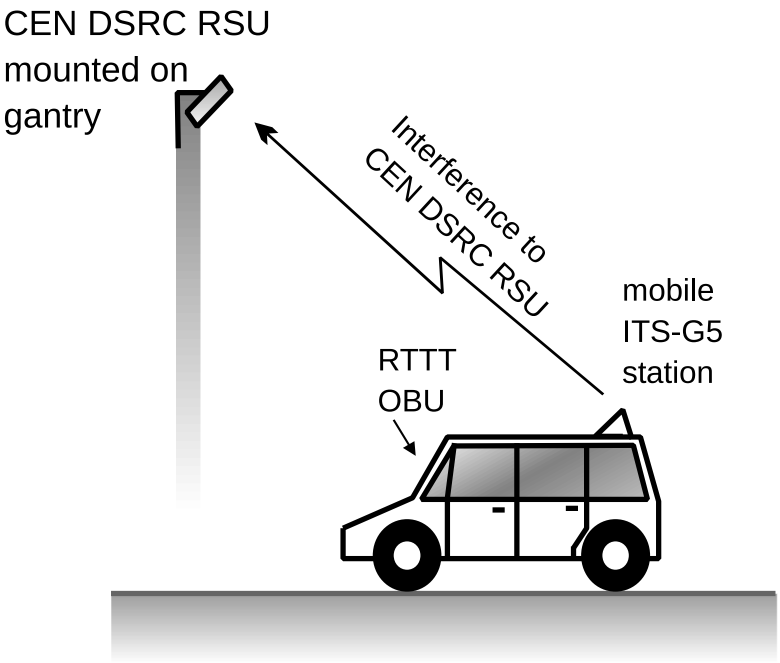


Figure 52: Blocking of CEN DSRC RSU or OBU, ITS mounted on car, CF#3

The geometry of the measurement setup is given by figure 52. It has to be chosen in a way that both, the CEN DSRC OBU and the ITS antenna are in the communication zone of the CEN DSRC RSU. The mounting of the ITS antenna and the CEN DSRC OBU is shown in figures 53 and 54.

Figure 53: Mounting of OBU and ITS antenna

Figure 54: Mounting of ITS antenna

6.2.6.1 OBU Interference power levels, ITS on rooftop

Table 26: Definition of TD_COEX_OBU_03

Identifier:	TD_COEX_OBU_03		
Summary:	OBU Interference for different duty cycles, car mounted position		
Configuration:	CF#3		
SUT	OBU		
Specification Reference:	CEN EN 12253 [i.3], CEN EN 13372 [i.2], CEN EN 15509 [i.6], ES 202 663 [i.5]		
Pre-test conditions:	• ITS unit sends with variable off times (T_{off}) • ITS unit sends with variable packet length • ITS TX power: Level well above recorded interfering level in TD_COEX_OBU_01 (+ 3 dB) • ITS positioned on the back part of the car roof • OBU positioned at the front window of the car • RSU positioned based on typical requirements • Stable communication between RSU and OBU (bit error rate approximately 10^{-6}) when ITS interference is inactive • ITS-G5A Channel: SCCH1 (5,875 GHz to 5,885 GHz) • CEN DSRC Channel: highest CEN DSRC channel 5,8125 GHz centre frequency and 5,815 GHz upper channel limit.		
Test Sequence:	**Step**	**Type**	**Description**
	1	stimulus	ITS unit sends with 29 dBm power value based on initial results with fixed on time and initial off time values as shown in table 27
	2	action	Record number of transactions as shown in table 6 and measure transaction duration and frame re-transmissions per transaction
	3	verify	Determine test verdict based on threshold TER Pass criteria per transaction: Transaction is complete Transaction duration < 100 ms Number of empty uplink frames < threshold value
	4	action	Change to next off time value
	5	loop	Repeat Step 2 to 4 until all off time values done

Table 27: Values for TD_COEX_OBU_03

Test TD_COEX_OBU_03 shall be executed with the following value combinations				
Sequence Number	**OBU Type**	**Car Type**	**T_{On} in µs**	**T_{Off} values in µs**
Test run 1	OBU10	SUV	1 000	3 000, 6 000, 9 000, 12 000, 18 000, 24 000, 30 000, 36 000
Test run 2	OBU12	SUV	176	3 000, 6 000, 9 000, 12 000, 18 000, 24 000, 30 000, 36 000
Test run 3	OBU12	SUV	1 000	3 000, 6 000, 9 000, 12 000, 18 000, 24 000, 30 000, 36 000, 50 000, 70 000, 100 000
Test run 4	OBU12	SUV	10 000	3 000, 6 000, 9 000, 12 000, 18 000, 24 000, 30 000, 36 000

6.2.7 Measurement 4: Multiple interferer using ITS system emulator

The measurement 4 setup consists of 5 real ITS stations which have been configured using the following parameters:

- Power output: 22,3 dBm e.i.r.p.
- Message size: see table 28
- Message duty cycle: see table 28

The ITS stations are positioned around the vehicle in a distance of around 5 m to 10 m. Furthermore, one ITS station is installed on top of the victim vehicle. The setup should allow for the emulation of real traffic situations with very high traffic density around the CEN DSRC victim system as given in table 28. In all scenarios the TX power in e.i.r.p. is 22,3 dBm.

Table 28: ITS scenarios for multiple interferer demonstration

Scenario	Emulated number of Vehicles	Duty Cycle [%]	Rate [Mbps]	Message Size in Byte	TX interval [ms]
Low Density	5	1,3	6	200	100
Medium Density	25	6,6	6	200	20
High Density	50	13,3	6	200	10
Extra long Duty Cycle	50	66	6	1 000	10

The ITS interference stations should mainly be installed in front of the victim car in order to model a worst case scenario. The RSU OBU link was operated in mode B (sensitivity limit).

The basic setup is depicted in figure 55 with five ITS stations around the victim and one ITS station installed at the victim vehicle. Figure 56 shows the realisation of the basic setup in the measurement chamber.

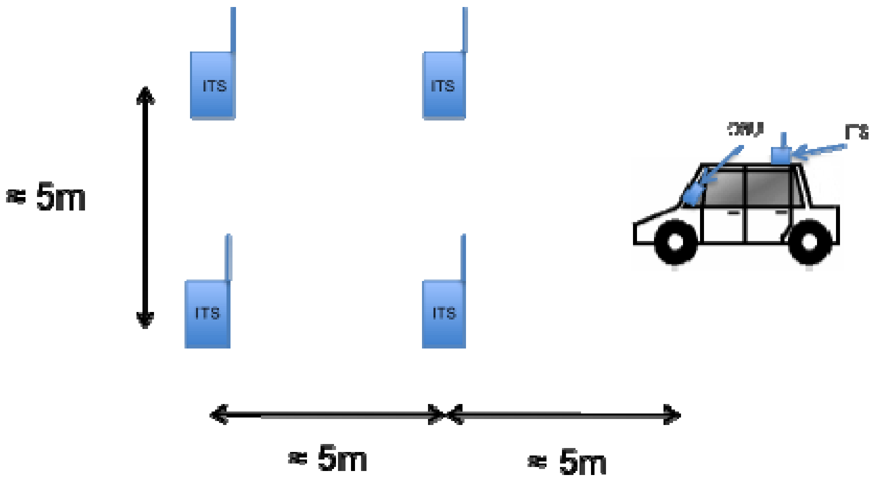


Figure 55: Measurement 4 basic setup, ITS demonstration

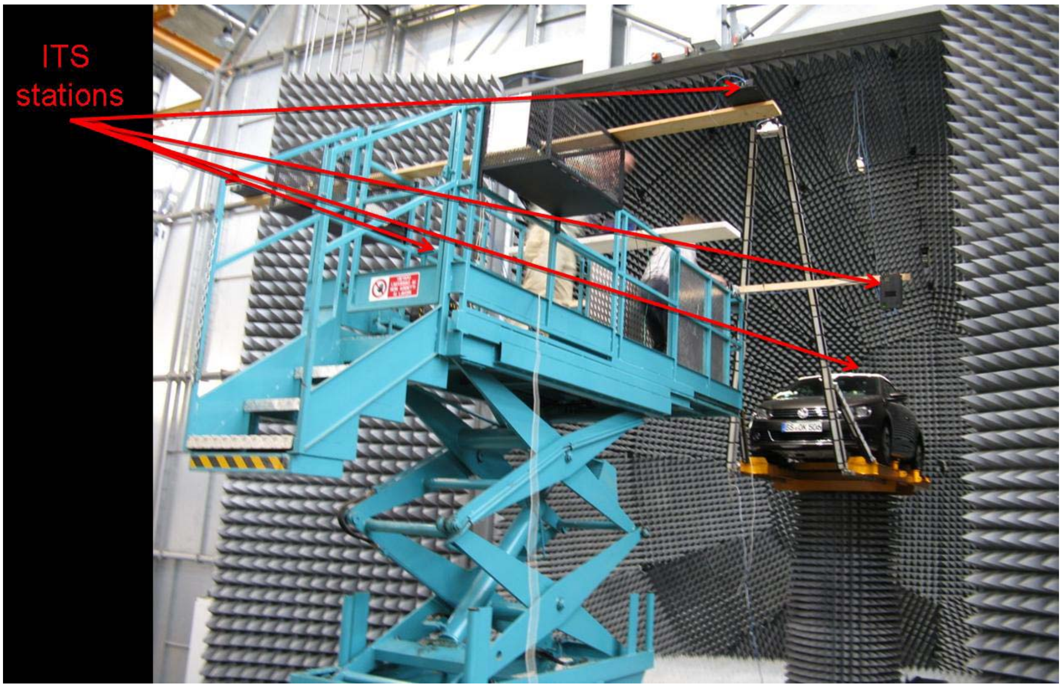


Figure 56: Measurement 4 real setup

6.3 Measurements Results

In this clause the results of the measurement in Ispra are presented. Also an initial evaluation of the results is presented here taking into account the car shielding measurements available. This adds some additional mitigation factors for the different interferer positions around the car.

6.3.1 Calibration

6.3.1.1 Measurements with a reference RX antenna (TD_CAL_01)

6.3.1.1.1 Test run and evaluation details

For three different types of cars (a passenger car with closed and with open roof, and an SUV) the antenna characteristic of a circular polarised patch antenna mounted behind the windscreen was measured with a ITS-G5 signal with a centre frequency of 5,88 GHz in azimuth and elevation.

The values shown in figures 57 and 58 are the total channel power levels for 100 % duty cycle measured at the connector of the substitution antenna.

More details and results can be found in clause A.2.1.

6.3.1.1.2 Azimuth scan

Due to reflections on the metal hull of the cars the antenna characteristic is not smooth when sweeping the azimuth angle. Even small angle variations of one degree can result in more than 15 dB difference in the received signal power level (see figure 57). The curve fit represents the empirical expected value resulting from a local average. Depending on the resulting radio channel (line of sight / non line of sight) this expected value can differ by more than 10 dB from the real value. For the relevant line of sight case this difference lays in the range of 0 dB to 6 dB.

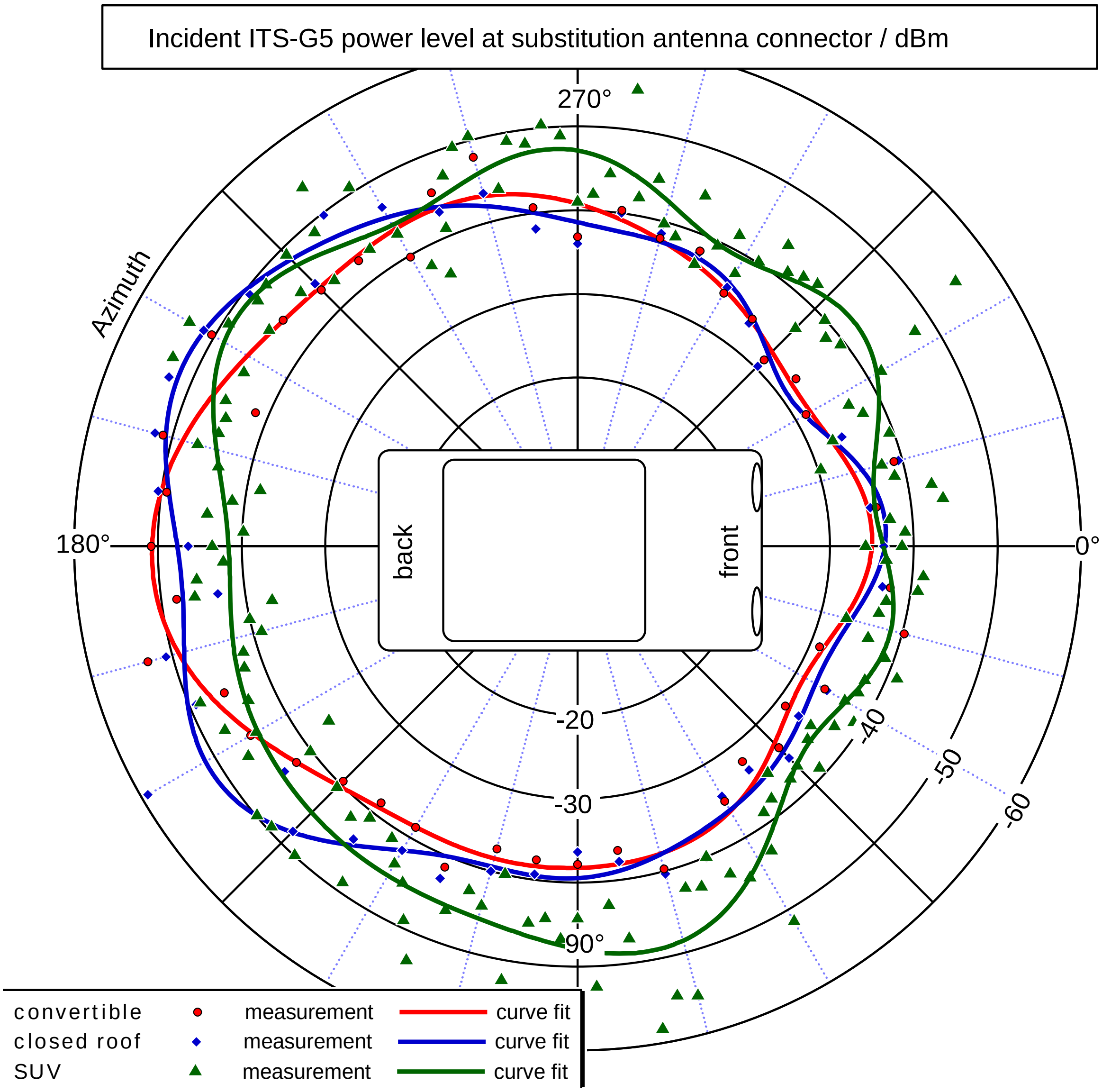


Figure 57: Comparison of substitution antenna azimuth characteristics for different vehicle types

6.3.1.1.3 Elevation scan

Due to reflections on the metal hull of the cars the antenna characteristic is not smooth when sweeping the elevation angle. Even small angle variations of one degree can result in more than 10 dB difference in the received signal power level (see figure 58). The curve fit represents the empirical expected value resulting from a local average. Depending on the resulting radio channel (line of sight / non line of sight) this expected value can differ by more than 6 dB from the real value (see figure 58).

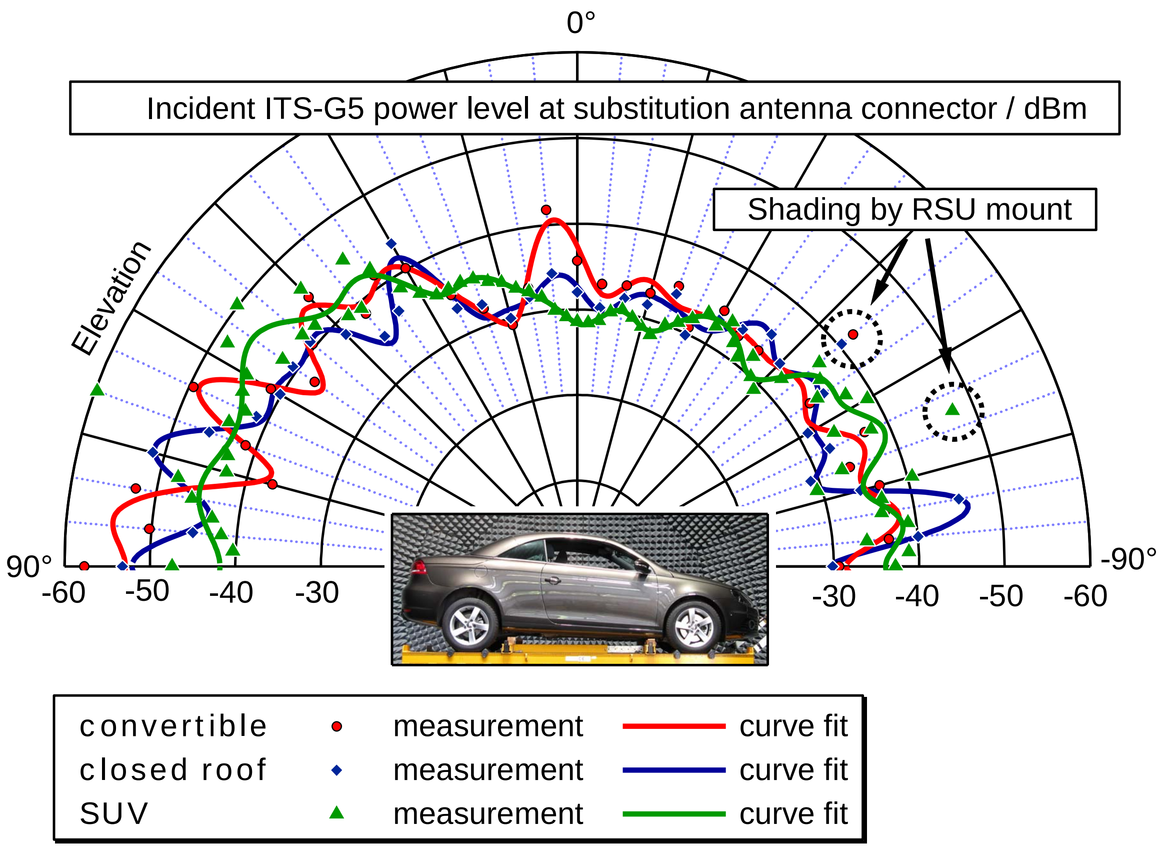


Figure 58: Comparison of substitution antenna elevation characteristics for different vehicle types

6.3.1.2 CEN DSRC power level at OBU position (TD_CAL_02)

6.3.1.2.1 Test run and evaluation details

For the convertible with closed roof and the SUV setup the CEN DSRC RX power level behind the windscreen was measured for different power level settings of the RSU. The LHCP measurement antenna was placed at the OBU position and directed towards the RSU.

The RSU was configured to CEN DSRC channel 4 with a centre frequency of 5,8125 GHz.

The RX power level was measured with the channel power measurement function of a spectrum analyzer with the setup shown in table 29.

Table 29: Setup of the spectrum analyzer used for the measurement of the CEN DSRC power level

Parameter	Value
Span	10 MHz
VBW	30 kHz
CH-Power BW	5 MHz
RBW	100 kHz
Ref. level	-40 dBm

The test setup was de-embedded according to equation 7 by use of the values listed in table 30.

$$P_A = Att_c - G_A + P_{RX} \quad (7)$$

Table 30: Symbols used in equation 7

Description	Symbol	Value
RX antenna gain	G_A	3 dBi
Cable attenuation	Att_c	1 dB
CEN DSRC RX power level	P_{RX}	measured value
CEN DSRC RX power level at OBU antenna	P_A	evaluated from equation 7

6.3.1.2.2 CEN DSRC power level at OBU mounted in the convertible

Table 31 shows the measured CEN DSRC power level at the OBU mounting position in the convertible. The ratio between the measured power level and the value set at the RSU is not constant due to the fact that the RSU is not a calibrated measurement device, but a commercial product with reasonable tolerances.

Table 31: Measured CEN DSRC power level at OBU mounted in the convertible

RSU Power setting P_S	Measured P_{RX}	CEN DSRC RX Power level P_A at OBU antenna
dBm	dBm	dBm
33	-32,7	-34,7
32	-33,7	-35,7
31	-34,7	-36,7
30	-36,0	-38,0
29	-36,7	-38,7
28	-37,0	-39,0
27	-37,7	-39,7
26	-40,4	-42,4
25	-41,7	-43,7
24	-43,6	-45,6
23	-44,4	-46,4
22	-44,0	-46,0
21	-45,2	-47,2
20	-46,0	-48,0
19	-47,6	-49,6
18	-48,4	-50,4
17	-49,4	-51,4
16	-51,2	-53,2
15	-52,2	-54,2
12	-55,6	-57,6

6.3.1.2.3 CEN DSRC power level at OBU mounted in the SUV

Table 32 shows the measured CEN DSRC power level at the OBU mounting position in the SUV and the spectrum analyzer setup for each measurement point.

Table 32: Measured CEN DSRC power level at OBU mounted in the SUV

RSU Power setting P_S	Measured P_{RX}	CEN DSRC RX Power level P_A at OBU antenna	Spectrum analyzer setup	
			preamplifier	reference level
dBm	dBm	dBm	--	dBm
12	-61,0	-63,0	on	-40
15	-57,0	-59,0	on	-40
16	-56,3	-58,3	on	-40
16	-56,0	-58,0	on	-40
17	-54,1	-56,1	on	-40
18	-53,2	-55,2	on	-40
20	-50,8	-52,8	on	-40
21	-50,0	-52,0	on	-40
22	-48,8	-50,8	on	-40
23	-47,2	-49,2	on	-40
24	-46,2	-48,2	on	-40
25	-44,3	-46,3	on	-40
26	-43,2	-45,2	off	-40
27	-40,6	-42,6	off	-40
28	-39,7	-41,7	off	-35
29	-39,3	-41,3	off	-35
30	-38,6	-40,6	off	-35

6.3.1.3 CEN DSRC BER for interferer from the front (TD_CAL_03)

6.3.1.3.1 Test run and evaluation details

The BER results for each OBU type were deduced from measurement 1. The OBUs were used in their typical mounting position (The truck OBUs tied flat to the windscreen, the multi purpose OBUs in their dedicated car-holder in the convertible, and in the truck-holder in the SUV).

Since measurement 1 was done with different CEN DSRC power levels, depending on the OBU sensitivity level (Mode A or Mode B - see clause 6.2.4), the results (see clause A.2.3.2) cannot be compared directly. Additionally, due to the antenna pattern of the OBU the sensitivity level depends on the angle towards the RSU. Hence, the mounting geometry influences the sensitivity. Even for the same OBU the results cannot be directly compared for different mounting geometries.

A way to compare the results, is to calculate the interference power limit for a certain CEN DSRC power level in front of the OBU. In previous work [i.4] this interference power limit was defined by the ITS-G5 power level that degrades the BER of the CEN DSRC link is to 10^{-5}.

A more practical way of comparing the results is to estimate the influence of a interference signal on the communication zone length of a tolling system. The interference signal can be seen as additional noise and thereby reducing the sensitivity of the CEN DSRC OBU (This assumption was confirmed by previous measurements [i.9]). From this sensitivity and the OBU mounting geometry the communication zone length can be estimated.

First a typical RX power level profile when passing the communication zone is assumed. This power level function over position depends on the RSU antenna pattern. This patterns is manufacturer specific, but the limits for the output power level and the antenna pattern are given in CEN EN 12253 [i.3]. Using these limits, a representative tolling station geometry, and some antenna theory, a typical incident RSU power level for each OBU position can be deduced (see figure 59 and [i.9]).

The properties of a typical CEN DSRC OBU antenna pattern are also specified in CEN EN 12253 [i.3]. Using again some antenna theory, the OBU mounting geometry, and a typical windscreen attenuation of 3 dB, the power level equivalent to a signal from OBU boreside can be calculated from the incident RSU power level for each position. If this equivalent signal level is higher than the OBU sensitivity (measured in boreside) the BER will be below 10^{-6} and the CEN DSRC communication works fine. Figure 59 shows the equivalent power levels for a truck OBU mounted in 2 m height with antenna boreside parallel to the street and a multipurpose OBU at the same position in a holder with 45° tilt.

By determining the length of the region where the equivalent power level is above the sensitivity limit, the length of the communication zone can be estimated for different OBU mounting geometries.

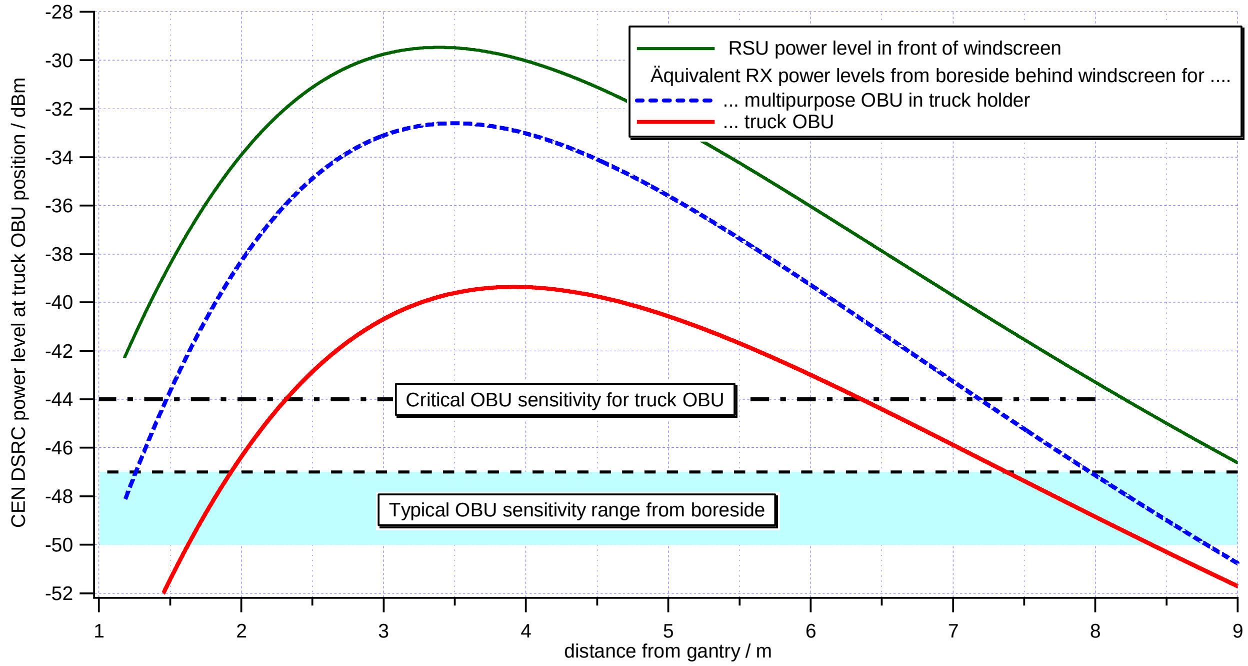


Figure 59: CEN DSRC incident power level for a given distance from a typical free flow toll gantry

The critical upper bound of the OBU sensitivity for this typical scenario results from the required communication zone length of 4 m for trucks and 5 m for cars. Figure 60 shows this length as function of the OBU sensitivity for a car OBU mounted under 60° tilt in 1 m height and for the two different truck OBUs from figure 59.

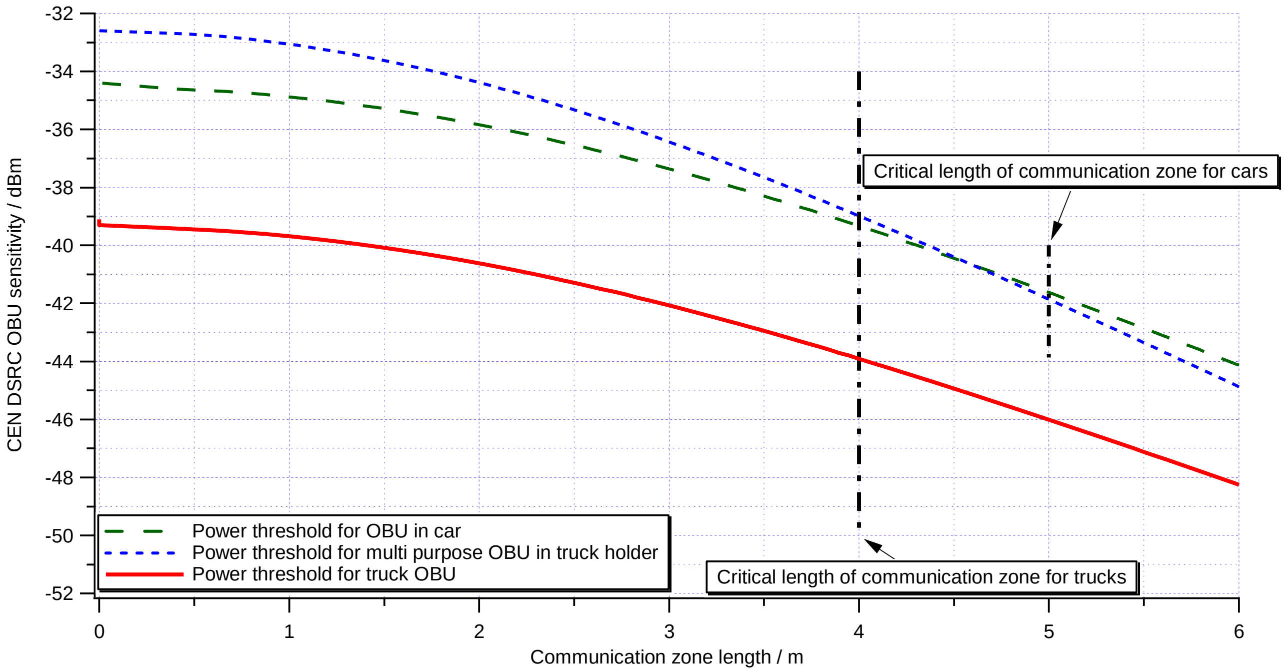


Figure 60: Relation between OBU sensitivity and communication zone length for a typical free flow toll gantry

As already mentioned the antenna patterns are manufacturer specific, but the physics behind them are always the same, therefore the absolute power levels involved in these estimations will not vary more than ± 2 dB. But more important than the absolute power thresholds in this estimation is the fact that a small change in OBU sensitivity will have a big impact on the communication zone length. For the most critical truck mounted OBUs the sensitivity level difference between a communication zone length of 4 m and no communication is less than 5 dB. Therefore typical OBUs exhibit a sensitivity level of -47 dBm or better to have some reasonable back off. This has to be kept in mind when it comes to the definition of interference limits.

Coming back to the evaluation of the measurement results.
Following steps have been taken:

- Evaluation of the BER values:
  - Determination of the incident CEN DSRC power level P_A from the RSU power setting P_S by use of calibration tables 31 and 32.
  - Determination of the interference power level P_{itf} from measurement 1 (see clause A.2.3.2) at which the BER is 10^{-5} (interference power limit).
- Normalisation to a fixed incident CEN DSRC power level of $P_{A\,Norm}$ = -47 dBm at OBU:
  - Determination of the power offset P_{off} between $P_{A\,Norm}$ and P_A (equation 8).
  - Calculation of the normalised interference limit $P_{itf\,Norm}$ from P_{off} and P_{itf} (equation 9).
- Communication zone length estimation.
  Determine the interference power limits for the used mounting geometry:
  - Determination of the OBU sensitivity P_s for the required communication zone length from figure 60.
  - Determination of the power offset P_o between P_s and P_A (equation 10).
  - Calculation of the interference limit $P_{itf\,cs}$ for the used mounting geometry and the required communication zone length (equation 11).

Equations used for the evaluation:

$$P_{off} = P_{A\,Norm} - P_A \quad (8)$$

$$P_{itf\,Norm} = P_{off} + P_{itf} \quad (9)$$

$$P_o = P_s - P_A \quad (10)$$

$$P_{itf\,cs} = P_o + P_{itf} \quad (11)$$

6.3.1.3.2 Comparison of interference limits of different OBU types

As already explained in the previous clause, the results from measurement 1 cannot be compared directly. Two methods have been applied to deduce comparable interference power limits from the measured values.

The first method corrects for the different incident CEN DSRC power levels P_A at the OBU used for each measurement run by normalising the results to a fixed value of $P_{A\,Norm}$ = -47 dBm. This value was chosen, since it corresponds to the typical sensitivity value of a CEN DSRC OBU. The result shows that the normalised interference power limit $P_{itf\,Norm}$ in front of the windscreen is almost independent of the OBU type, but is strongly influenced by the mounting geometry (OBU2 and OBU9 where of same type, but differently mounted). In cars, where the OBUs are mounted flat on the windscreen, the normalised interference limit in front of the windscreen was measured to be around -43 dBm. In trucks the OBUs are either mounted in a tilted holder or tied directly to the windscreen. For both mounting methods and for four different OBU types the normalised interference limit evaluated from the measurement results lies in the range between -50 dBm and -52 dBm.

The second method to compare the measurement results, is to take the operational requirements on the investigated OBUs as criteria. The most important criteria to ensure a sufficient CEN DSRC transaction performance is the communication zone length. Since the transaction time is fixed, the necessary length depends on the vehicle speed. Therefore 4 m length is sufficient for trucks and 5 m necessary for cars that can drive faster. In the previous clause the communication zone length as function of the OBU sensitivity and three typical mounting geometries was estimated.

To meet the communication zone requirements, an interference signal from the front, was estimated to not exceed -38 dBm for a 60° tilted car mounted OBU, -43 dBm for a truck mounted OBU in a 45° tilted holder, and -49 dBm for a truck mounted OBU attached directly to the windscreen without tilt (0°). Since this estimation is based on several assumptions on the geometry of multilane free flow tolling stations and a number of RSU and OBU properties, the absolute values might vary by ± 2 dB. Additionally, the length of the communication zone is very sensitive to a small change of the interference signal power level. Therefore the interference power limit of 0,11 V/m (-52 dBm) in front of the windscreen, as found by previous theoretical work [TR][TS], can be confirmed by the measurements and by both comparison methods. All results are summarized in table 33.

Table 33: Comparison of the interference limits for different OBU types and mounting geometries evaluated from measurements performed with an interfering ITS-G5 station in front of the CEN DSRC OBU

OBU			Veh. type	P_S	P_A	P_{itf}	P_{off}	$P_{itf\ Norm}$	P_s	P_o	$P_{itf\ cs}$
Type	**use**	**Mounting**		**dBm**	**dBm**	**dBm**	**dB**	**dBm**	**dBm**	**dB**	**dBm**
OBU11	multi purpose	with car holder	car	21	-47,2	-43,0	0,2	-42,8	-42	5,2	-37,8
OBU2	truck	flat on screen	car	22	-46	-41,9	-1	-42,9	-42	4	-37,9
OBU10	multi purpose	with truck holder	SUV	26	-45,2	-47,8	-1,8	-49,6	-39	6,2	-41,6
OBU12	multi purpose	with truck holder	SUV	23	-49,2	-53,1	2,2	-50,9	-39	10,2	-42,9
OBU6	truck	flat on screen	SUV	23	-49,2	-53,3	2,2	-51,1	-44	5,2	-48,1
OBU9	truck	flat on screen	SUV	23	-49,2	-54,5	2,2	-52,3	-44	5,2	-49,3

6.3.2 Measurement 1: OBU Interference sensitivity pattern

6.3.2.1 Test run and evaluation details

In measurement 1 the CEN DSRC BER as function of the interference power level was determined for different interferer positions. Details of the test setup are listed in table 22.

The raw measurement data processing is described in clause A.3. In the following clauses the resulting interference power levels and their impact on the number of interfering ITS stations are shown. The results cannot be compared directly, as discussed in clause 6.3.1.3.1. But they show how different the interference behaviour for different scenarios can look like.

The interference power limit shows strong fluctuations over azimuth caused by fading. This fading region was evaluated from the measurement results by statistic methods and a DFT filter to obtain a curve fit. If too less points for a statistic analysis were available, the fading region was roughly estimated according to the statistics of a similar test run.

From the interference power limit a diagram was evaluated, that shows the distance over azimuth that an interferer with a certain TX power level should be away to cause no harmful interference to the CEN DSRC communication. The isolation over distance underlying these diagrams was calculated with the free space path loss model (equation A.2) and a path loss coefficient $n = 1,8$. In these diagrams the typical distances of cars driving at different speeds are shown for comparison with the interference ranges.

To get an impression how many ITS-G5 stations can possibly interfere to a CEN DSRC communication, the interference distance diagram for a certain ITS-G5 power level is overlaid to a figure of a motorway with three lanes in each direction. One lane is congested, the others are open and the cars are moving between 80 km/h and 130 km/h. When counting the number of possible interferers for this scenario for different ITS-G5 power levels, a steep increase of this number at high ITS-G5 power levels can be observed.

All results show that the fading effect has a strong influence on all results, and that the interference will follow a stochastic process. Therefore all diagrams show a range of probable results. The actual result will change rapidly over time and will touch all values within this range during one CEN DSRC frame. Therefore the worst case must be considered as interference level.

6.3.2.2 OBU sensitivity evaluation measurement (TD_COEX_OBU_01)

6.3.2.2.1 TD_COEX_OBU_01: Test run 1

The test run 1 was performed with OBU11 mounted in the convertible with closed roof. Details to the test setup and the test parameters are listed in tables 22 and 23.

This test run was performed with a CEN DSRC incident power level of -47,2 dBm. This is 6 dB above the sensitivity limit of OBU11 (Mode A).

The ITS-G5 transmit power level was swept from 28 dBm to 38 dBm. Unfortunately this range was smaller than the dynamic range of the interference limit. For several azimuth values the interference limit was either above or below the measurement range. These points are marked with triangles in figure 61. Nevertheless, a reasonable fading margin was estimated and used for further evaluation of the separation distance to guarantee the necessary isolation that ensures coexistence (figures 62, 63 and 64).

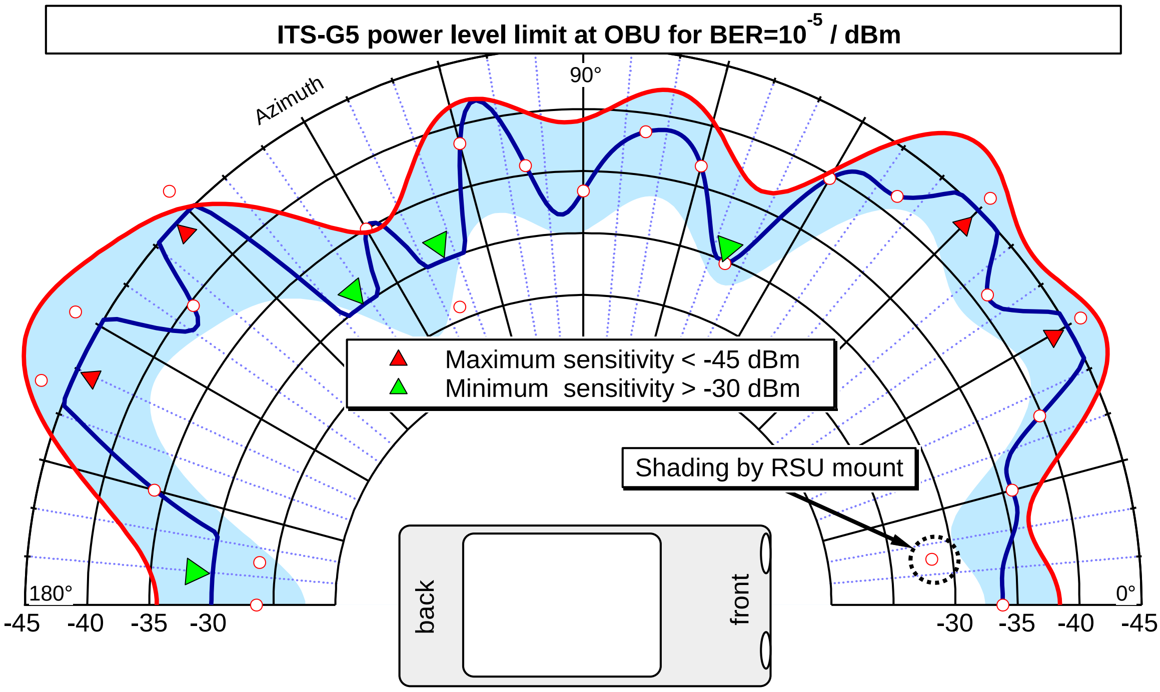


Figure 61: Interference limit for OBU11 mounted in a passenger car at 6 dB above sensitivity limit (DSRC incident power level -47,2 dBm), TD_COEX_OBU_01, test run 1

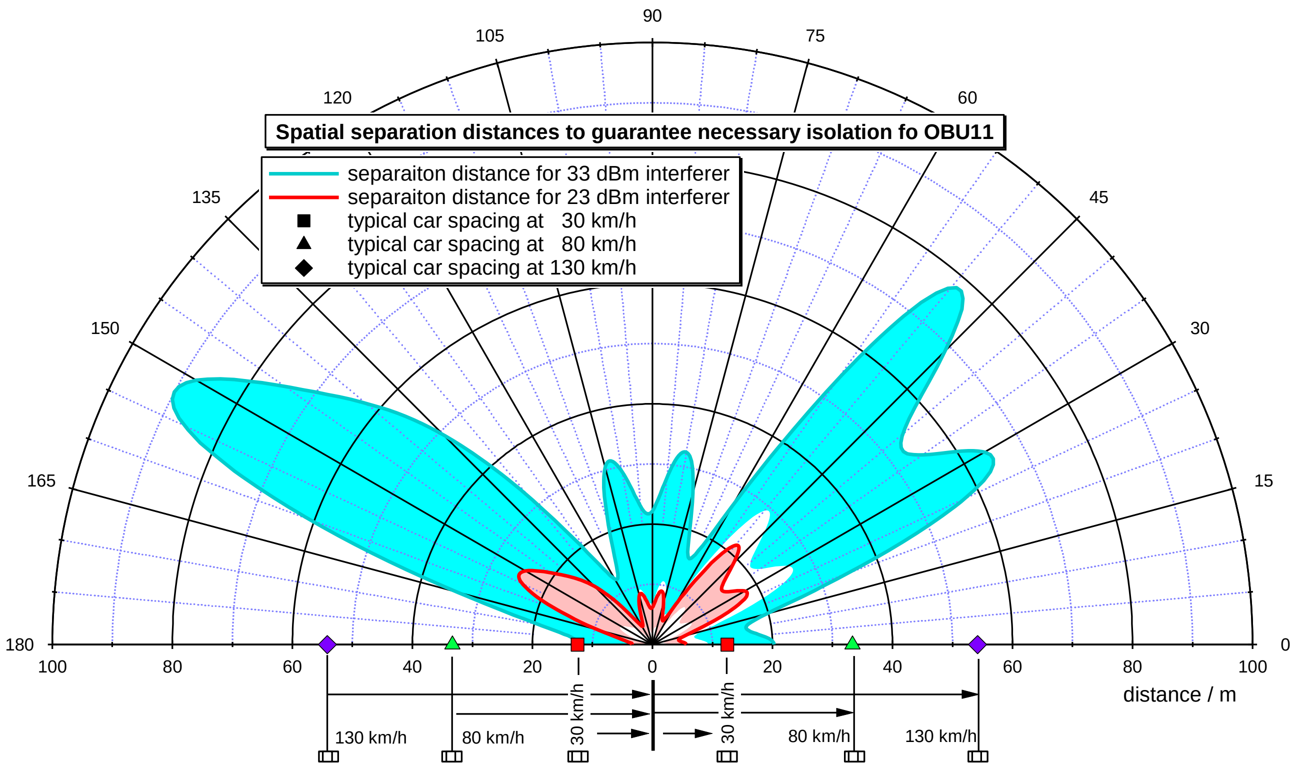


Figure 62: Separation distance to avoid interference to a car mounted OBU11, 6 dB above CEN DSRC sensitivity limit (DSRC incident power level -47,2 dBm), TD_COEX_OBU_01, test run 1

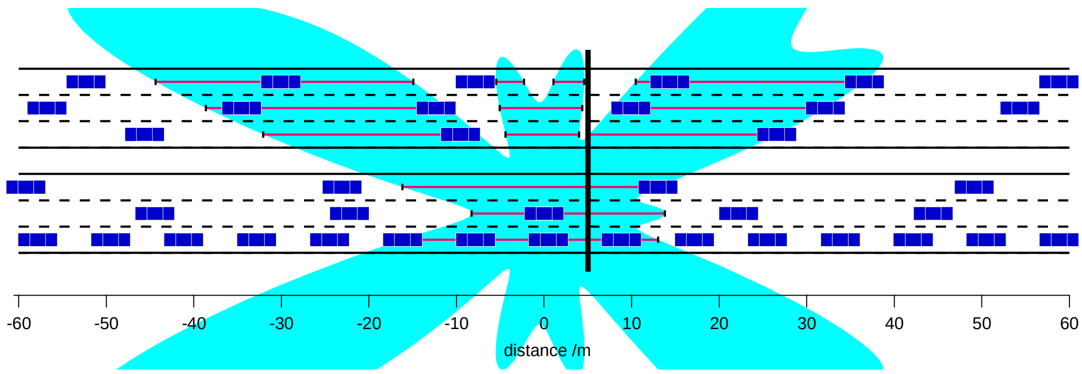


Figure 63: Interference region for a 30 dBm ITS-G5 signal and a car mounted OBU11, 6 dB above CEN DSRC sensitivity limit (DSRC incident power level -47,2 dBm), TD_COEX_OBU_01, test run 1

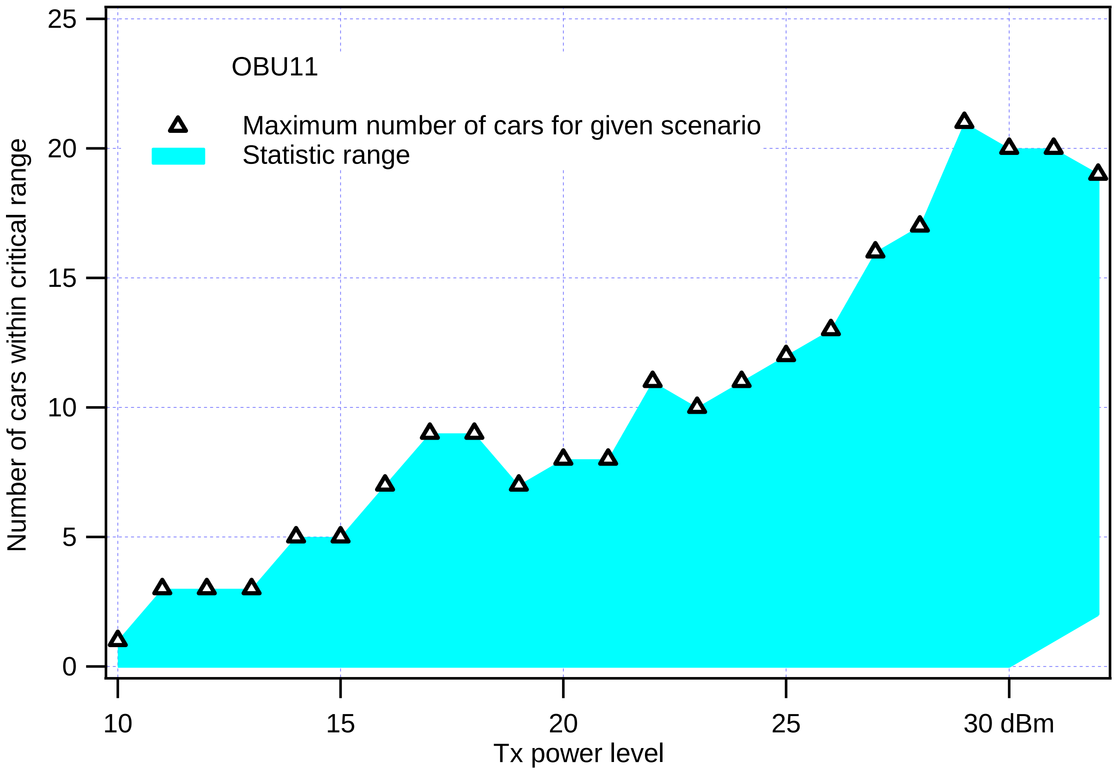


Figure 64: Number of possible interferers to the car mounted OBU11, 6 dB above CEN DSRC sensitivity limit (DSRC incident power level -47,2 dBm), for the traffic scenario shown in figure 63 as function of the ITS-G5 output power level, TD_COEX_OBU_01, test run 1

6.3.2.2.2 TD_COEX_OBU_01: Test run 2

The test run 2 was performed with OBU2 mounted in the convertible with closed roof. Details to the test setup and the test parameters are listed in tables 22 and 23.

This test run was performed with a CEN DSRC incident power level of -46 dBm at the sensitivity limit of OBU2 (Mode B).

The ITS-G5 transmit power level was swept from 19 dBm to 29 dBm. The azimuth was swept in 15° steps. Therefore, the fading margin could be roughly estimated only (figure 65). This estimation was used for further evaluation of the separation distance to guarantee the necessary isolation that ensures coexistence (figures 66, 67 and 68).

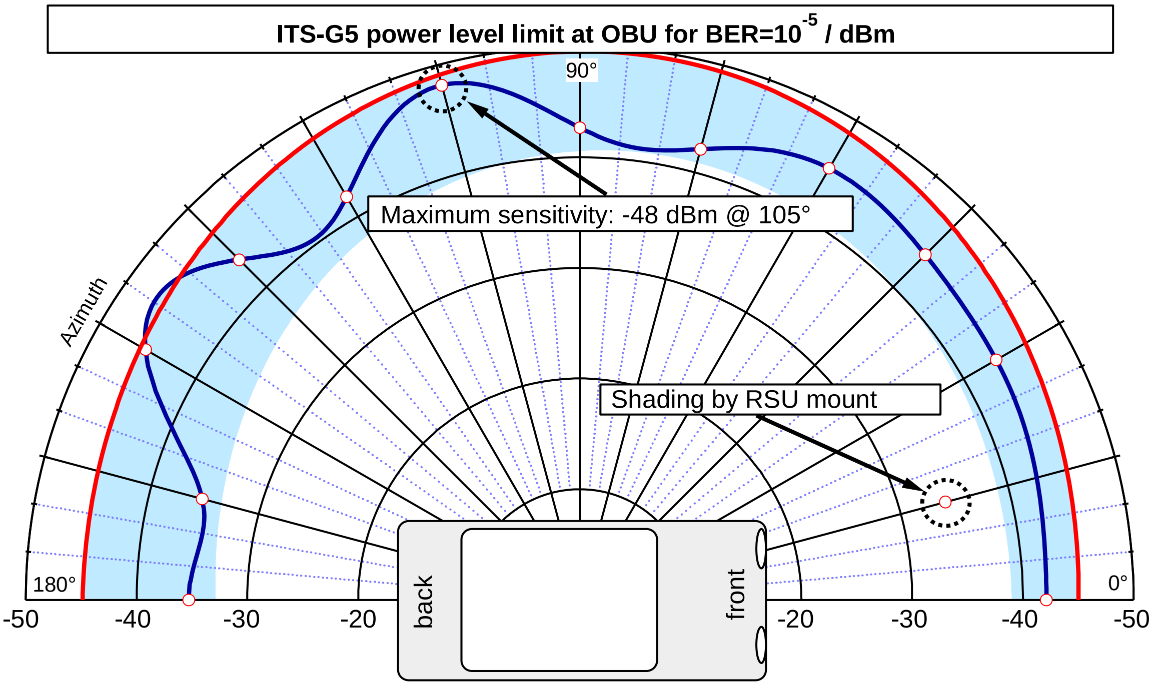


Figure 65: Interference limit for OBU2 mounted in a passenger car at sensitivity limit (DSRC incident power level -46 dBm),TD_COEX_OBU_01, test run 2

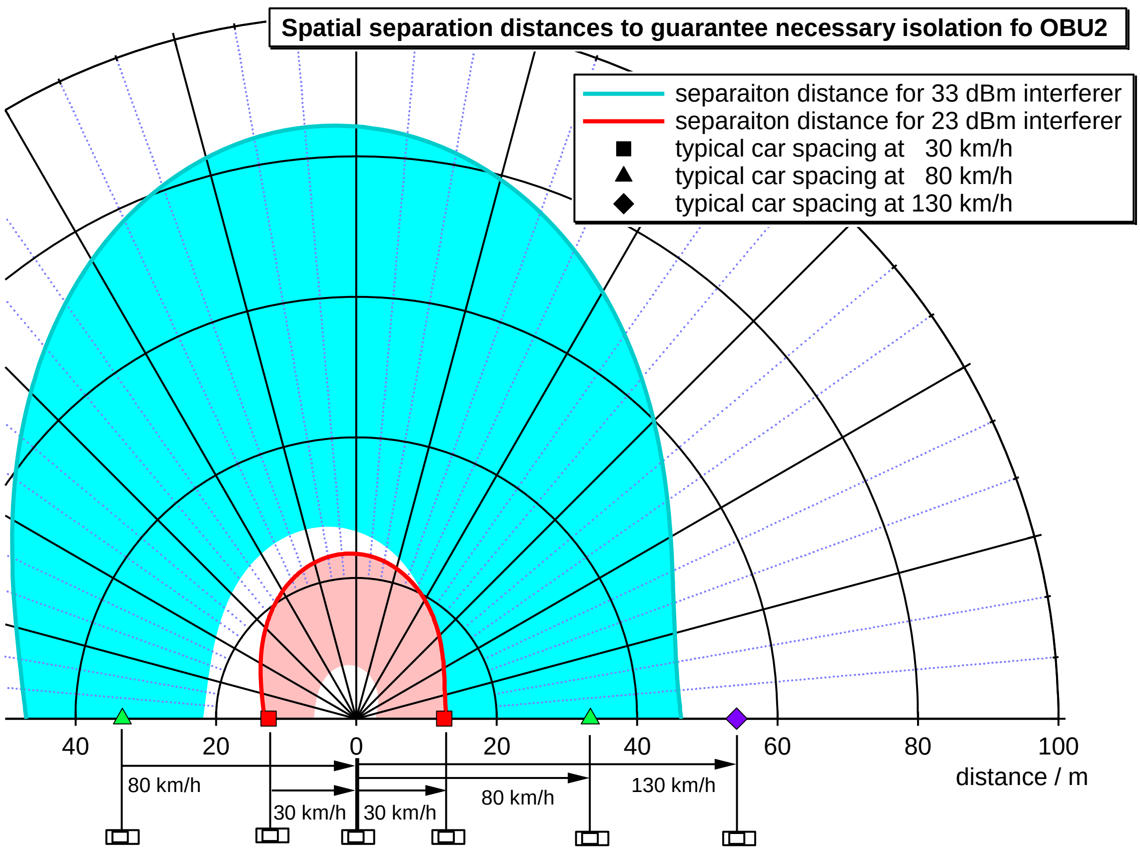


Figure 66: Separation distance to avoid interference to a car mounted OBU2, at CEN DSRC sensitivity limit (DSRC incident power level -46 dBm), TD_COEX_OBU_01, test run 2

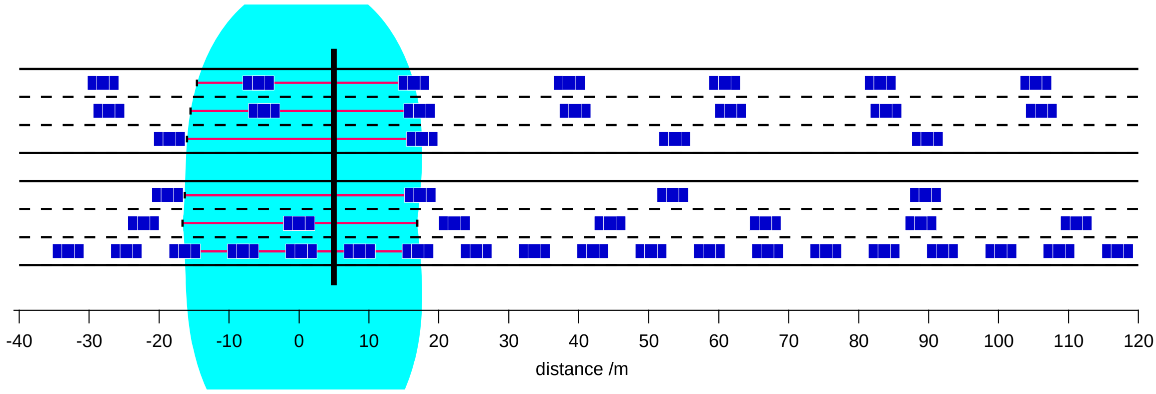


Figure 67: Interference region for a 25 dBm ITS-G5 signal and a car mounted OBU2, at CEN DSRC sensitivity limit (DSRC incident power level -46 dBm), TD_COEX_OBU_01, test run 2

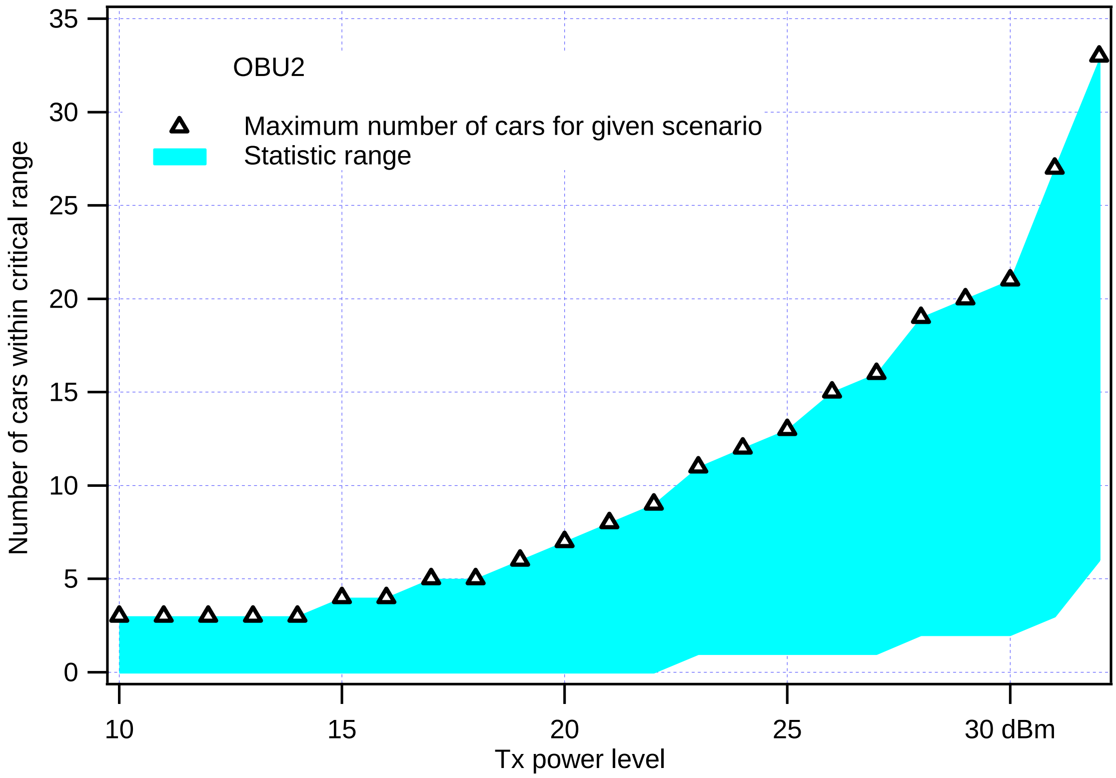


Figure 68: Number of possible interferers to the car mounted OBU2, at CEN DSRC sensitivity limit (DSRC incident power level -46 dBm), for the traffic scenario shown in figure 67 as function of the ITS-G5 output power level, TD_COEX_OBU_01, test run 2

6.3.2.2.3 TD_COEX_OBU_01: Test run 3

The test run 3 was performed with OBU10 mounted in the SUV. Details to the test setup and the test parameters are listed in tables 22 and 23.

This test run was performed with a CEN DSRC incident power level of -45,2 dBm at the sensitivity limit of OBU10 (Mode B).

The ITS-G5 transmit power level was swept from 15 dBm to 39 dBm. At some few azimuth values the interference limit exceeded even this large power range.

The azimuth was swept in 2° steps. Therefore, the fading margin could be very well estimated (figure 69). This estimation was used for further evaluation of the separation distance to guarantee the necessary isolation that ensures coexistence (figures 70, 71 and 76).

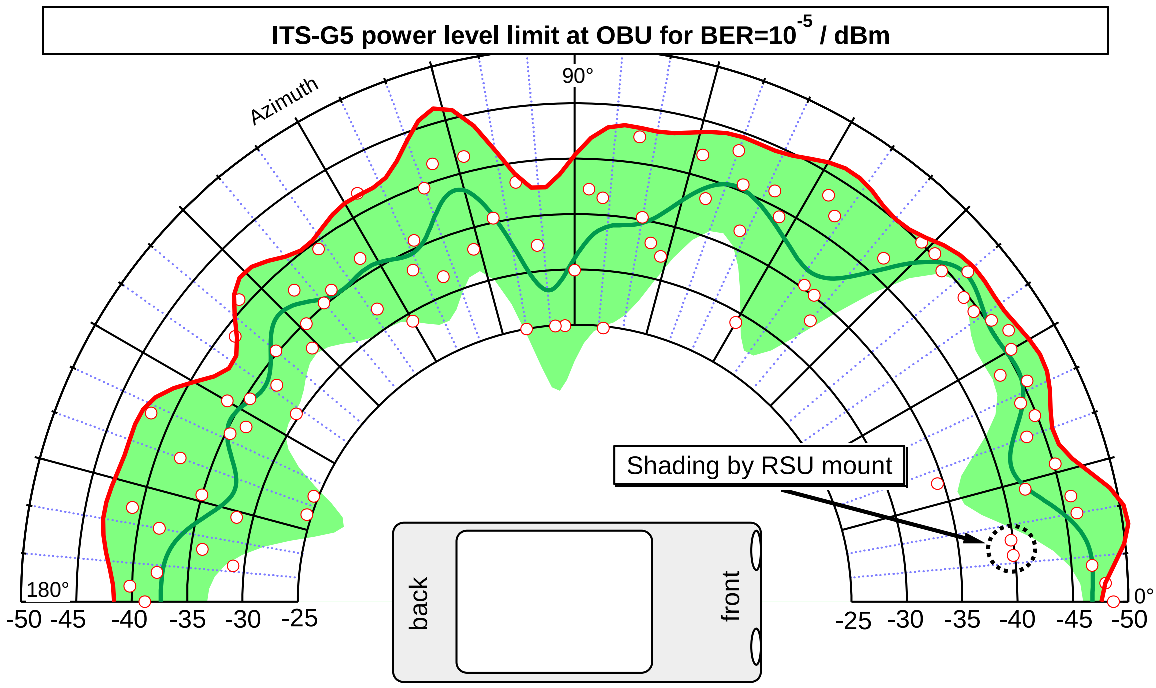


Figure 69: Interference limit for OBU10 mounted in an SUV at sensitivity limit (DSRC incident power level -45,2 dBm),TD_COEX_OBU_01, test run 3

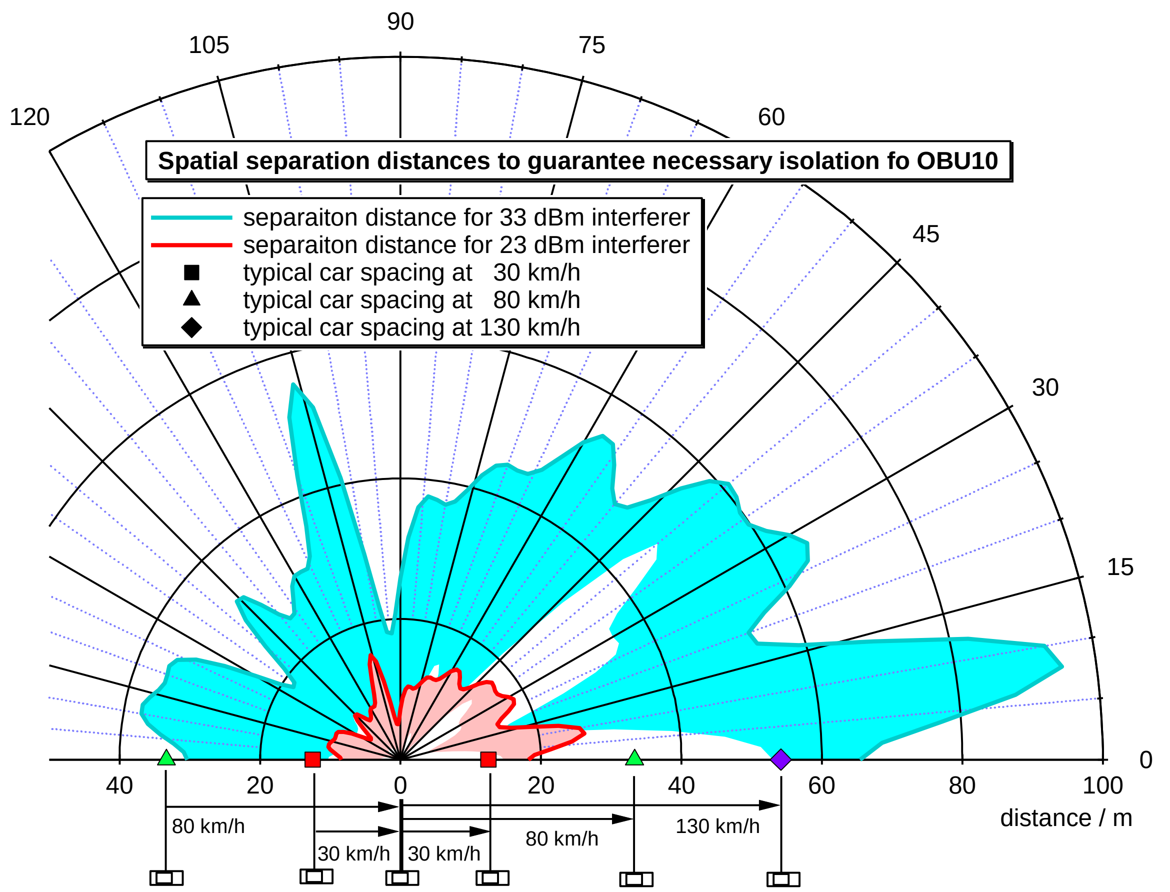


Figure 70: Separation distance to avoid interference to a SUV mounted OBU10, at CEN DSRC sensitivity limit (DSRC incident power level -45,2 dBm), TD_COEX_OBU_01, test run 3

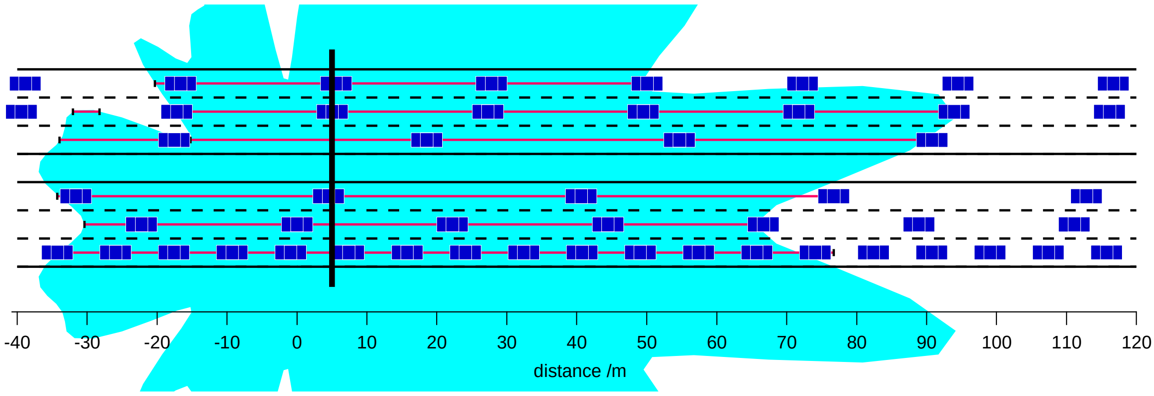


Figure 71: Interference region for a 33 dBm ITS-G5 signal and a SUV mounted OBU10, at CEN DSRC sensitivity limit (DSRC incident power level -45,2 dBm), TD_COEX_OBU_01, test run 3

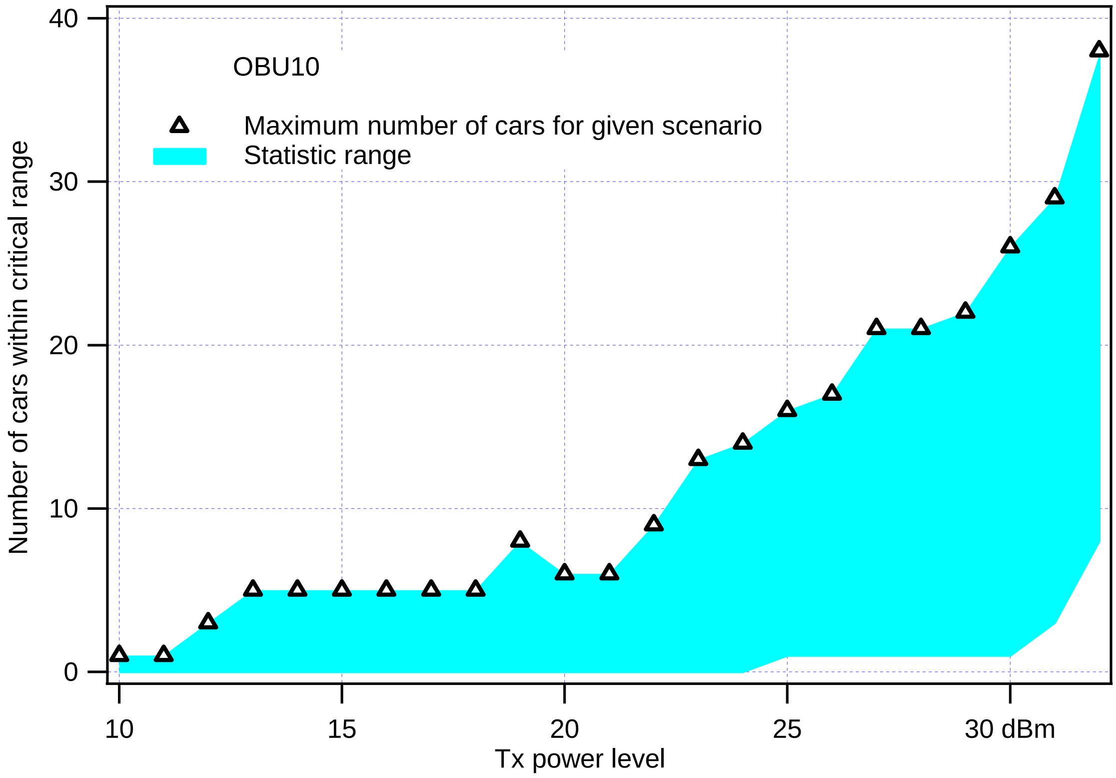


Figure 72: Number of possible interferers to the SUV mounted OBU10, at CEN DSRC sensitivity limit (DSRC incident power level -45,2 dBm), for the traffic scenario shown in figure 71 as function of the ITS-G5 output power level, TD_COEX_OBU_01, test run 3

6.3.2.2.4 TD_COEX_OBU_01: Test run 4

The test run 4 was performed with OBU12 mounted in the SUV. Details to the test setup and the test parameters are listed in tables 22 and 23.

This test run was performed with a CEN DSRC incident power level of -49,2 dBm at the sensitivity limit of OBU12 (Mode B).

The ITS-G5 transmit power level was swept from -5 dBm to 20 dBm. This range was only sufficient for the azimuth range from 0° to 45°. For higher azimuth values this range was exceeded and no measurement points are available there.

The azimuth was swept in 2° steps. Therefore, the fading margin could be very well estimated (figure 73). This estimation was used for further evaluation of the separation distance to guarantee the necessary isolation that ensures coexistence (figures 74, 75 and 76). Due to missing results to the side and to the back the diagrams are incomplete.

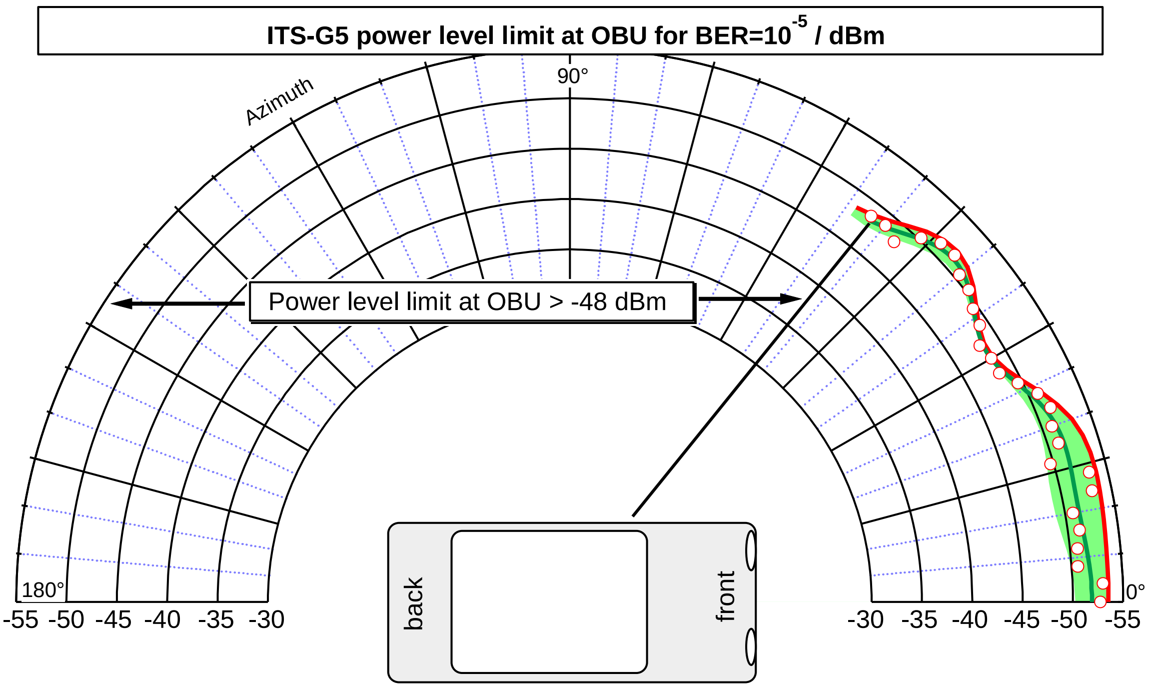


Figure 73: Interference limit for OBU12 mounted in an SUV at sensitivity limit (DSRC incident power level -49,2 dBm),TD_COEX_OBU_01, test run 4

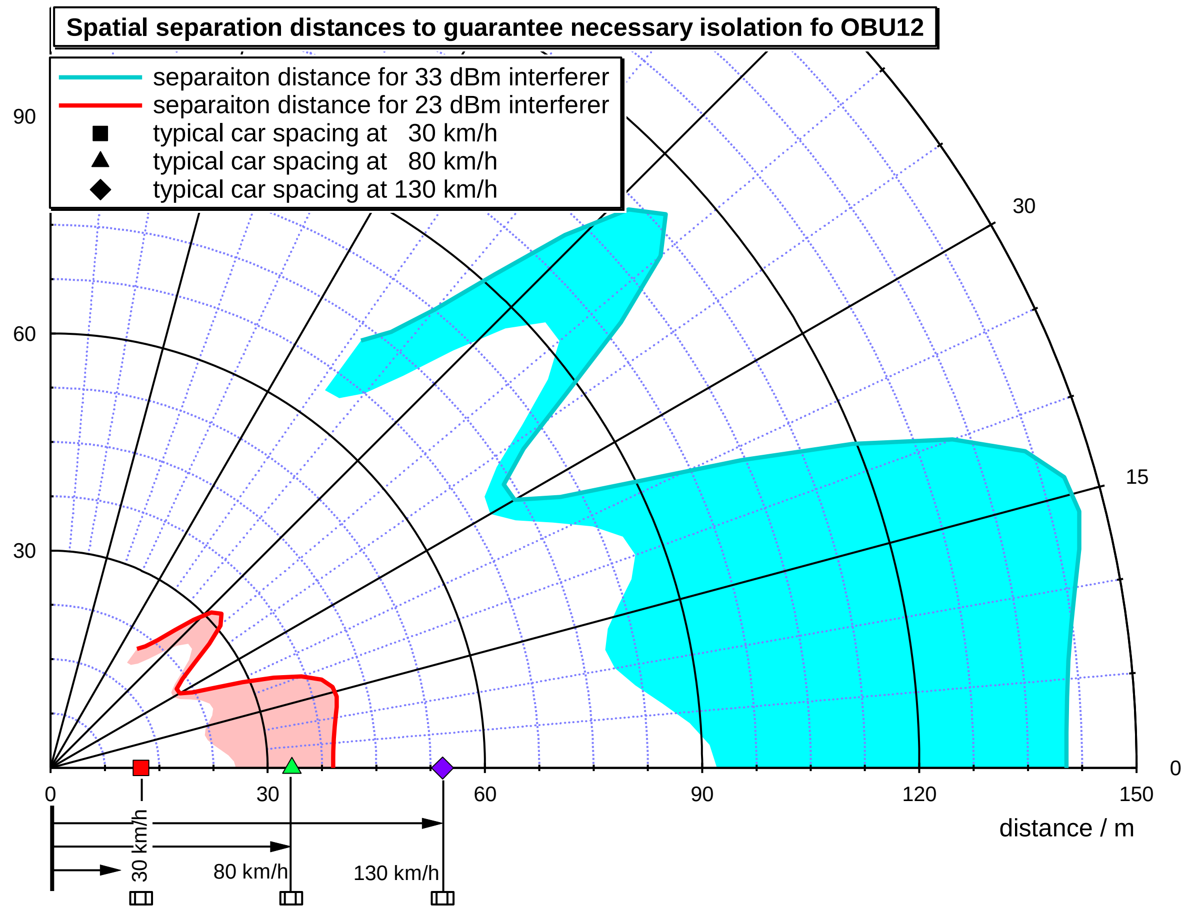


Figure 74: Separation distance to avoid interference to a SUV mounted OBU12, at CEN DSRC sensitivity limit (DSRC incident power level -49,2 dBm), TD_COEX_OBU_01, test run 4

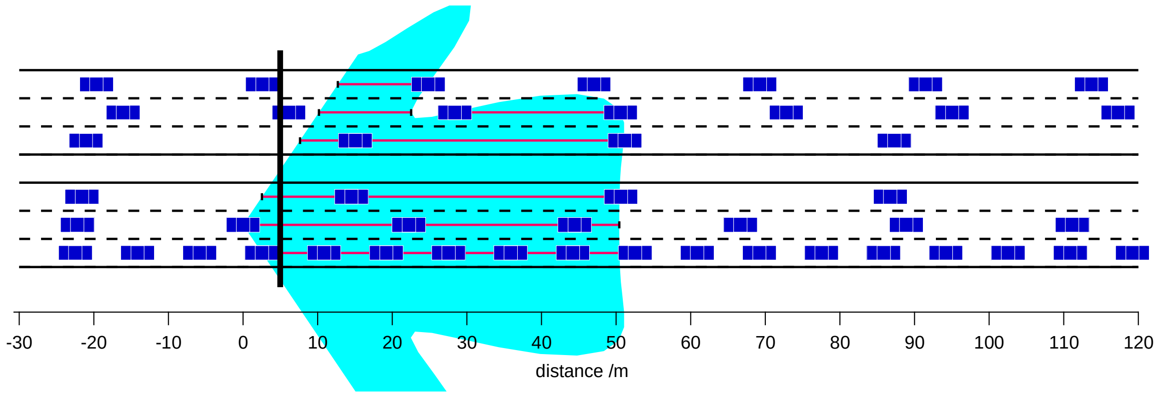


Figure 75: Interference region for a 25 dBm ITS-G5 signal and a SUV mounted OBU12, at CEN DSRC sensitivity limit (DSRC incident power level -49,2 dBm), TD_COEX_OBU_01, test run 4

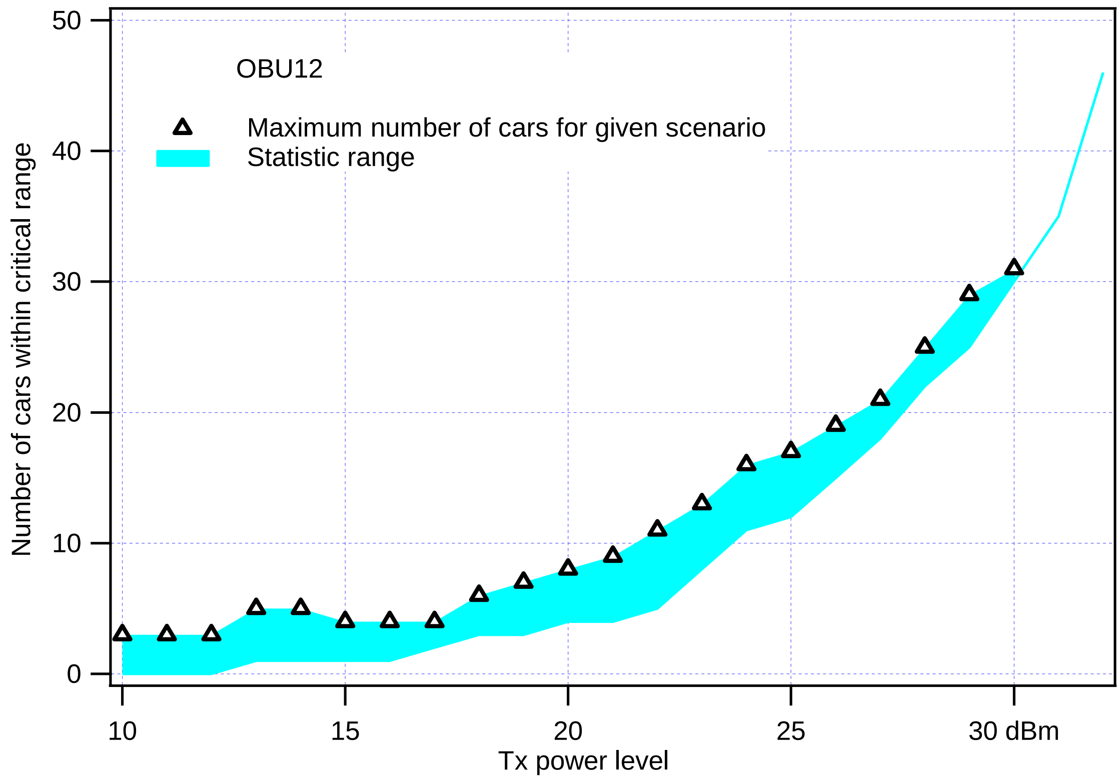


Figure 76: Number of possible interferers to the SUV mounted OBU12, at CEN DSRC sensitivity limit (DSRC incident power level -49,2 dBm), for the traffic scenario shown in figure 75 as function of the ITS-G5 output power level, TD_COEX_OBU_01, test run 4

6.3.2.2.5 TD_COEX_OBU_01: Test run 5

The test run 5 was performed with OBU6 mounted in the SUV. Details to the test setup and the test parameters are listed in tables 22 and 23.

This test run was performed with a CEN DSRC incident power level of -49,2 dBm at the sensitivity limit of OBU6 (Mode B).

The ITS-G5 transmit power level was swept from 13 dBm to 39 dBm. This range was not sufficient for all azimuth values. The azimuth regions where this range was exceeded and results are missing are marked by triangles in figure 77.

The azimuth was swept in 1° steps over 360°. Therefore, the fading margin estimation is excellent (figure 77). This estimation was used for further evaluation of the separation distance to guarantee the necessary isolation that ensures coexistence (figures 78, 79 and 80). Due to missing results to the side and to the back the diagrams are incomplete.

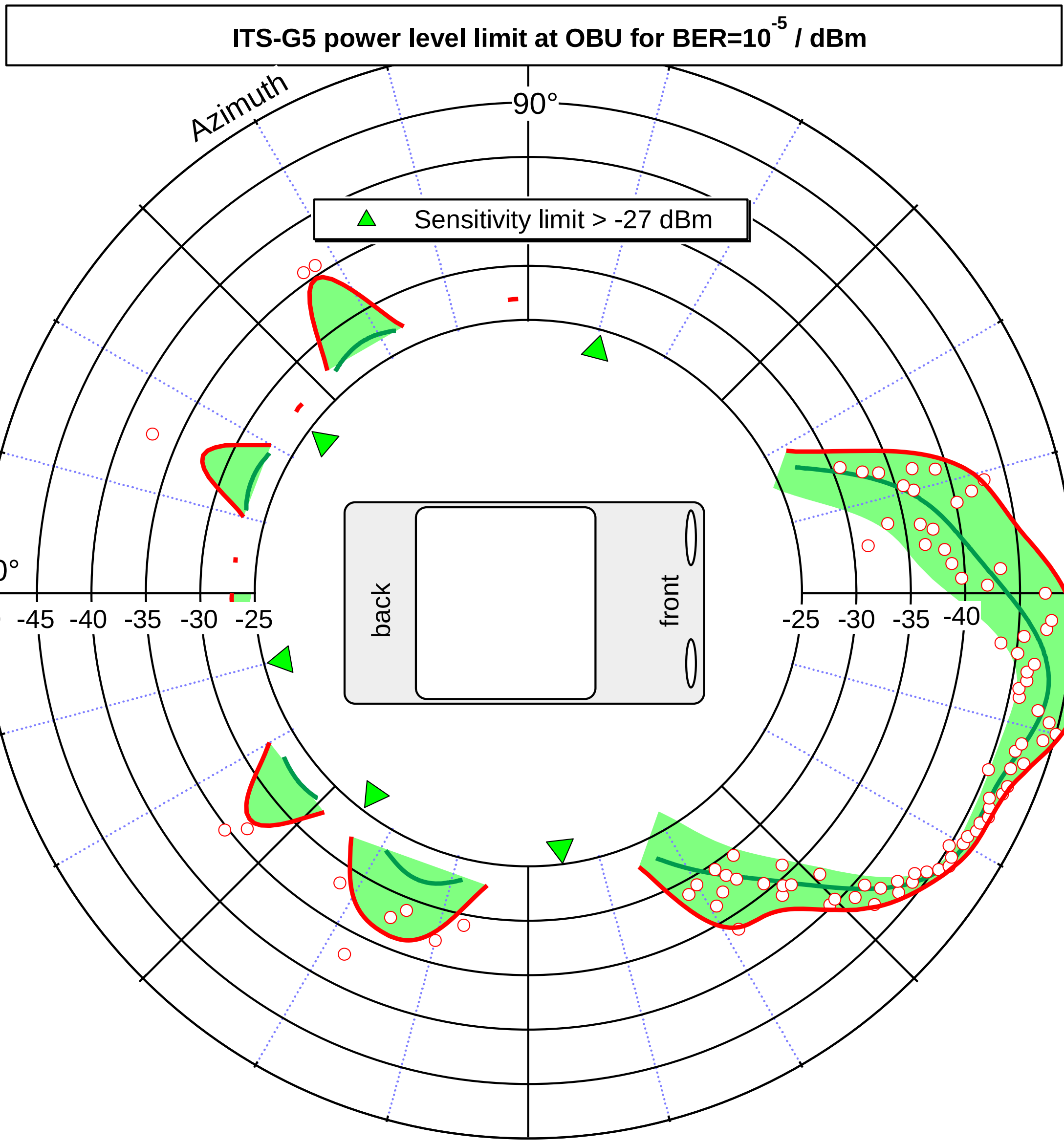


Figure 77: Interference limit for OBU6 mounted in an SUV at sensitivity limit (DSRC incident power level -49,2 dBm), TD_COEX_OBU_01, test run 5

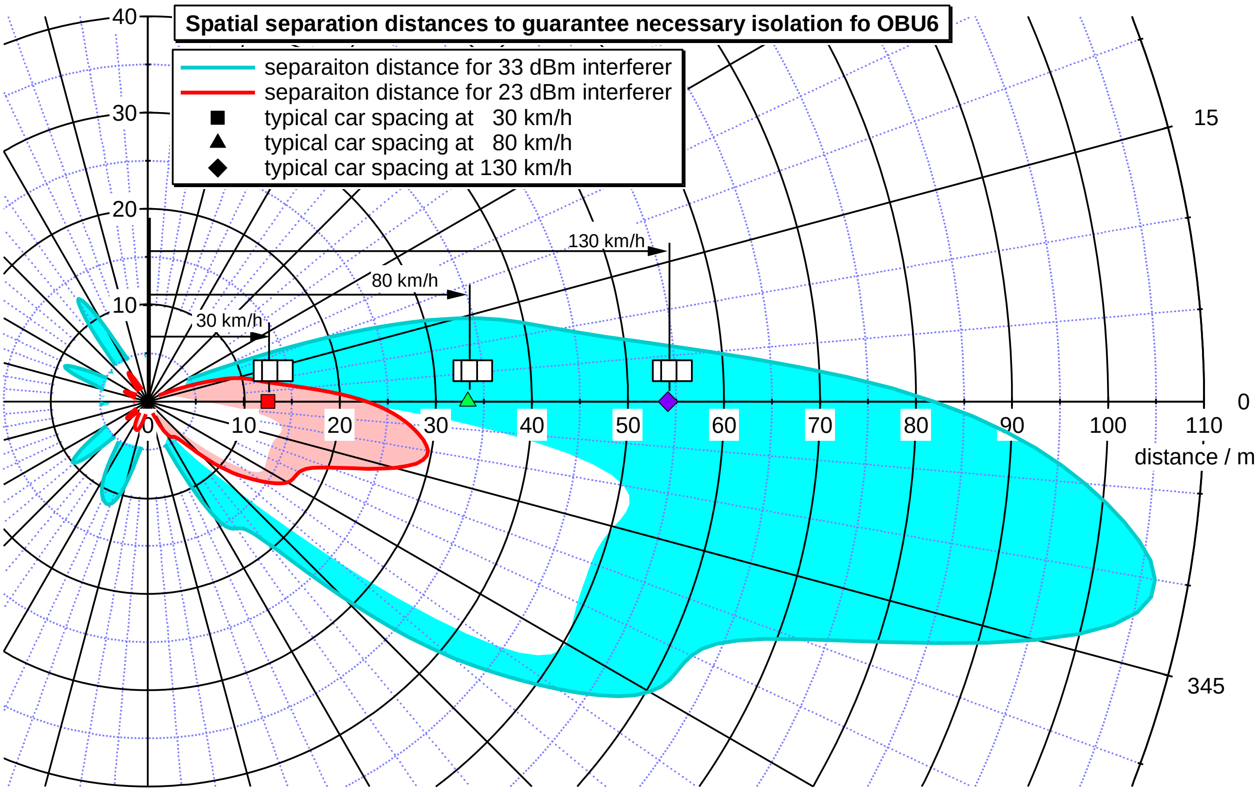


Figure 78: Separation distance to avoid interference to a SUV mounted OBU6, at CEN DSRC sensitivity limit (DSRC incident power level -49,2 dBm), TD_COEX_OBU_01, test run 5

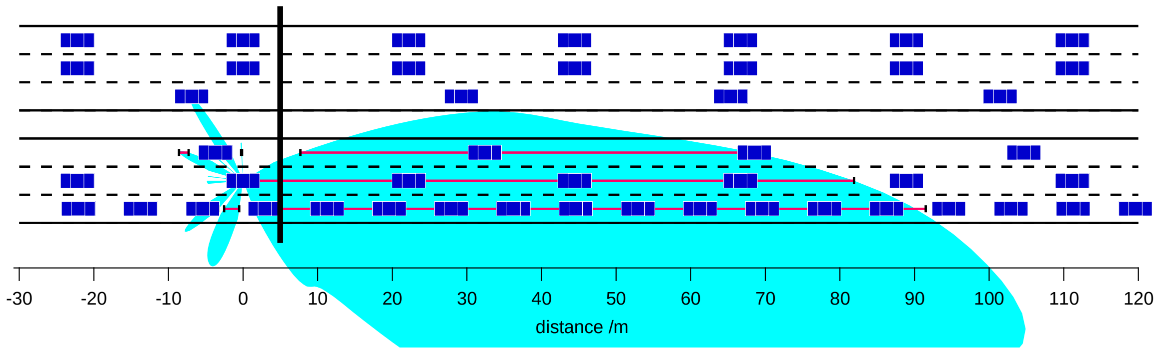


Figure 79: Interference region for a 33 dBm ITS-G5 signal and a SUV mounted OBU6, at CEN DSRC sensitivity limit (DSRC incident power level -49,2 dBm), TD_COEX_OBU_01, test run 5

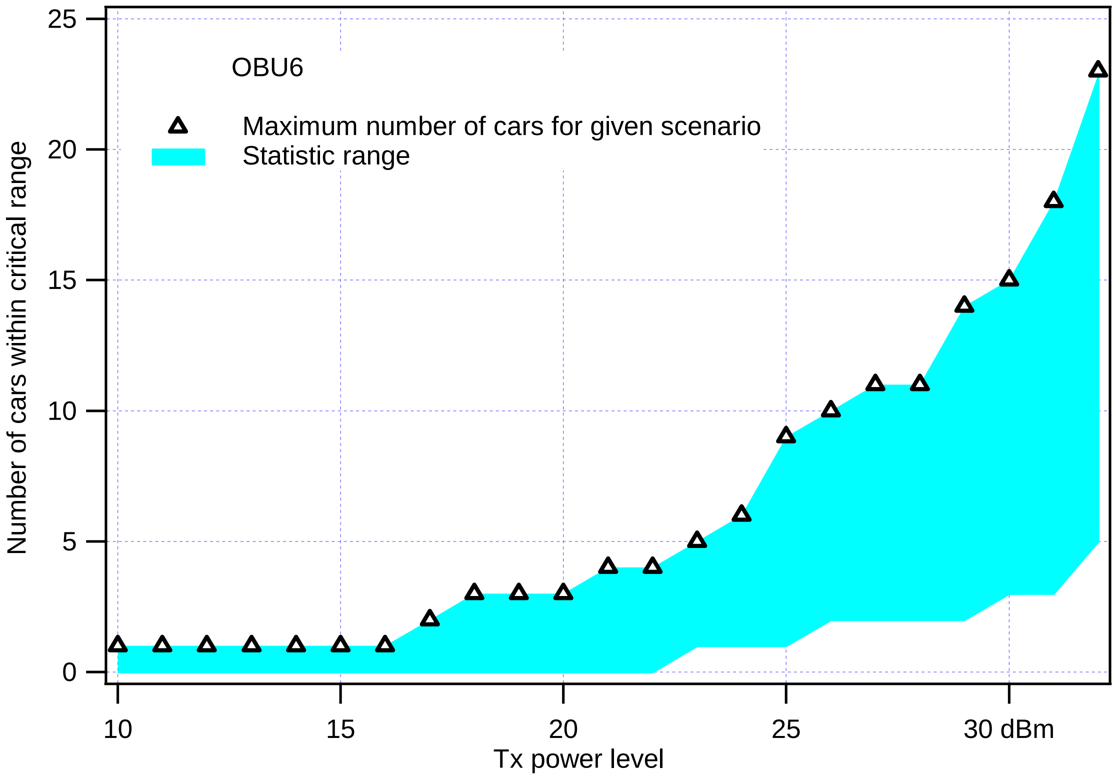


Figure 80: Number of possible interferers to the SUV mounted OBU6, at CEN DSRC sensitivity limit (DSRC incident power level -49,2 dBm), for the traffic scenario shown in figure 79 as function of the ITS-G5 output power level, TD_COEX_OBU_01, test run 5

6.3.2.2.6 TD_COEX_OBU_01: Test run 6

The test run 6 was performed with OBU9 mounted in the SUV. Details to the test setup and the test parameters are listed in tables 22 and 23.

This test run was performed with a CEN DSRC incident power level of -49,2 dBm at the sensitivity limit of OBU9 (Mode B).

The ITS-G5 transmit power level was swept from 9 dBm to 34 dBm. This range was not sufficient for all azimuth values. The azimuth regions where this range was exceeded and the results were set to the upper margin are marked by triangles in figure 81.

The azimuth was swept in 2° steps. Therefore, the fading margin could be very well estimated (figure 81). This estimation was used for further evaluation of the separation distance to guarantee the necessary isolation that ensures coexistence (figures 82, 83 and 84).

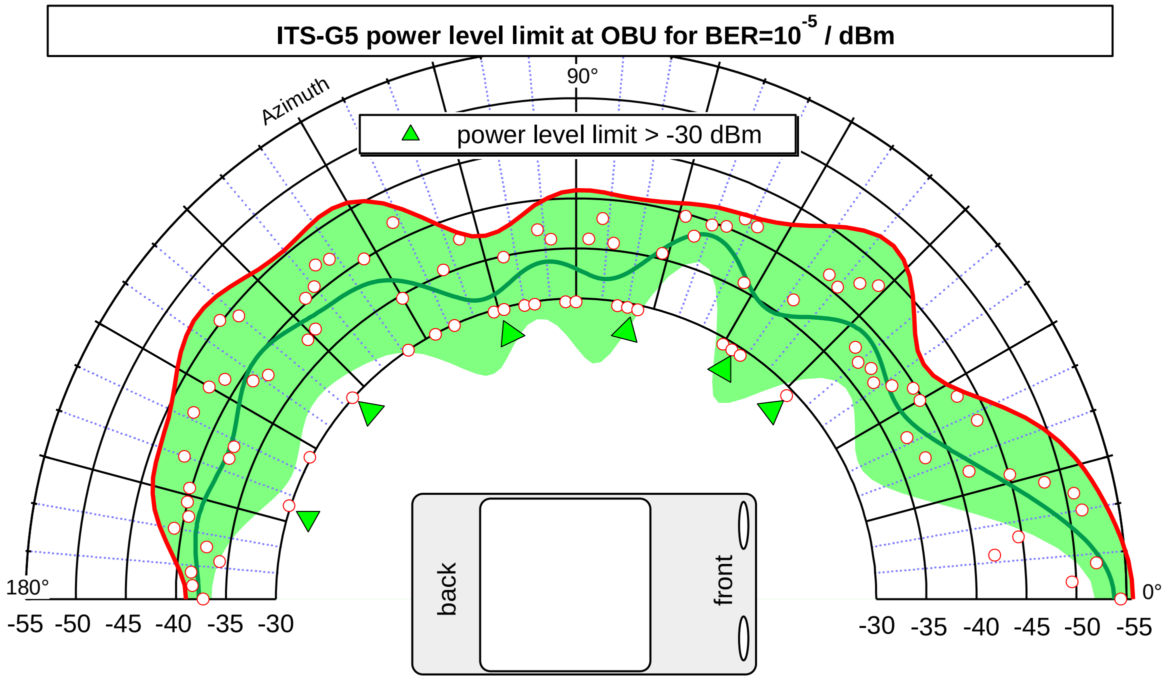


Figure 81: Interference limit for OBU9 mounted in an SUV at sensitivity limit (DSRC incident power level -49,2 dBm), TD_COEX_OBU_01, test run 6

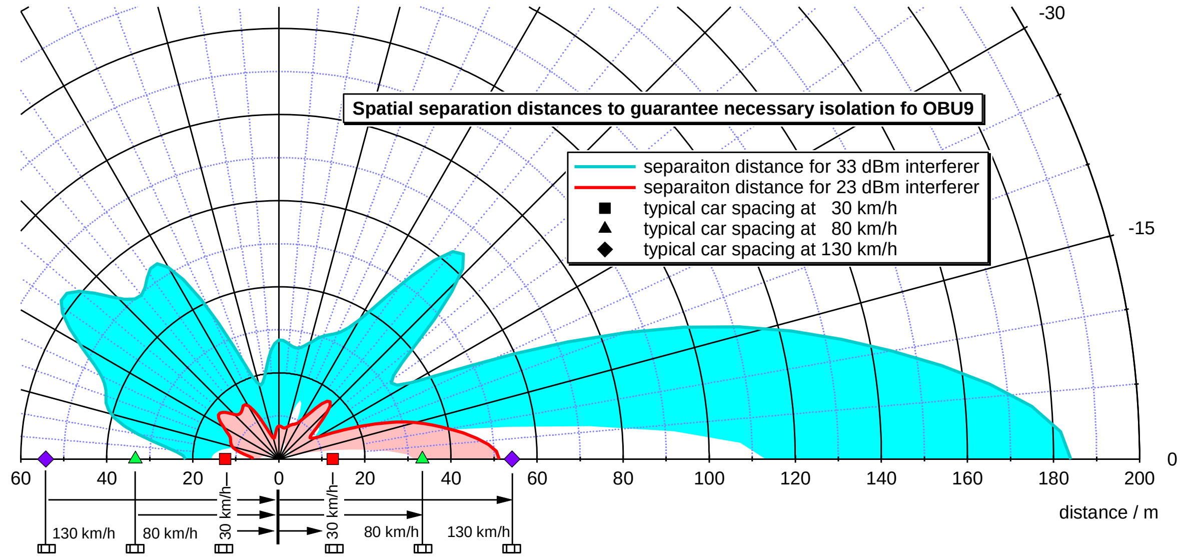


Figure 82: Separation distance to avoid interference to a SUV mounted OBU9, at CEN DSRC sensitivity limit (DSRC incident power level -49,2 dBm), TD_COEX_OBU_01, test run 6

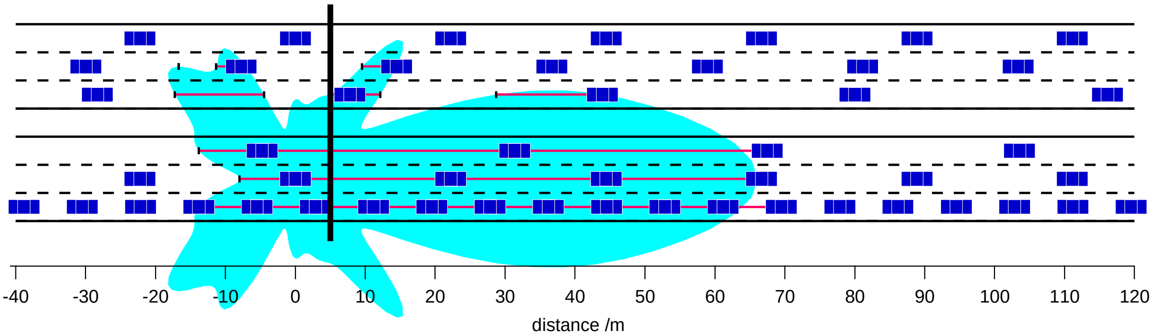


Figure 83: Interference region for a 25 dBm ITS-G5 signal and a SUV mounted OBU9, at CEN DSRC sensitivity limit (DSRC incident power level -49,2 dBm), TD_COEX_OBU_01, test run 6

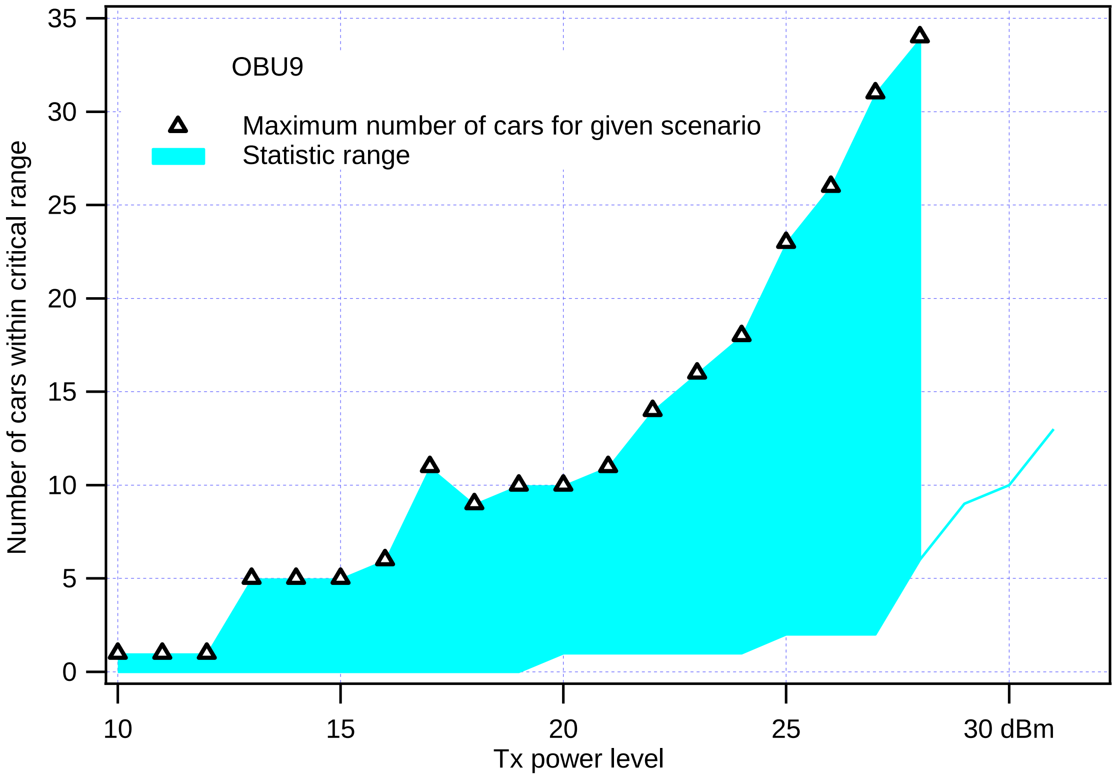


Figure 84: Number of possible interferers to the SUV mounted OBU9, at CEN DSRC sensitivity limit (DSRC incident power level -49,2 dBm), for the traffic scenario shown in figure 83 as function of the ITS-G5 output power level, TD_COEX_OBU_01, test run 6

6.3.3 Measurement 2: Single interferer with different duty cycles

6.3.3.1 Result evaluation and coexistence limits

The statistic properties of the transaction duration and the number of retransmissions were evaluated for a CEN DSRC transmission disturbed by a single interferer with different duty cycles. The duty cycle of the interferer was specified by the time with active transmission T_{on} and by the time T_{off} where the output power level was small enough to ensure coexistence (see figure 85). The ITS-G5 interferer was positioned in front of the SUV and behind the RSU, so that the interference signal was directed towards the CEN DSRCOBU antenna main lobe, but not towards the CEN DSRC RSU. Further details of the test setup and the test runs are listed in table 24.

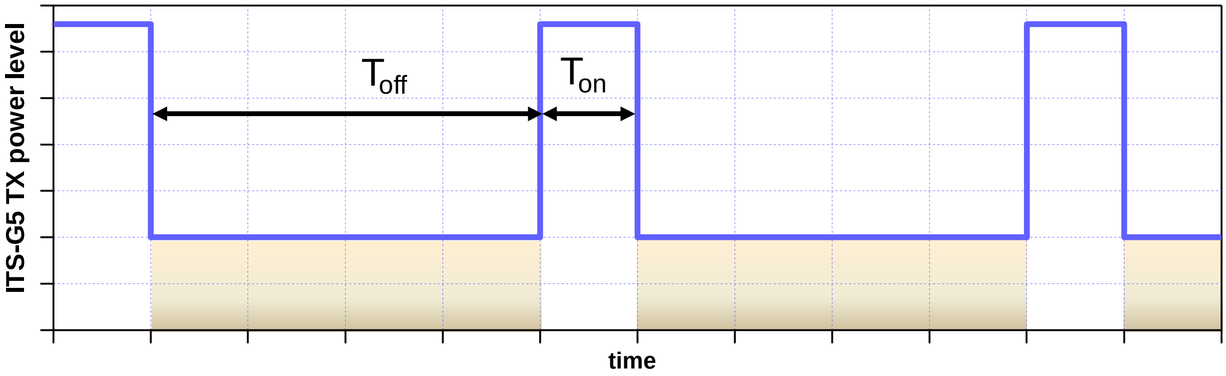


Figure 85: TX power level of a low duty cycle signal

To evaluate the statistic behaviour of the CEN DSRC system when disturbed by such a signal, 200 CEN DSRC tolling transactions were performed for each interference signal configuration and the number of CEN DSRC frame retransmissions as well as the transaction duration were evaluated for each transaction.

An empirical curve fit was used to calculate the relation between T_{on} and T_{off} for an expected value of one retransmission per transaction. To ensure coexistence of CEN DSRC and ITS-G5 the number of CEN DSRC retransmissions for one multilane free flow tolling transaction should be less than one in average. For this reason T_{on} should be shorter than the CEN DSRC frame length plus the retransmission turnaround time. For the toll system used in this test, the upper limit of T_{on} was 5 ms. For the same reason a T_{off} time shorter than the toll transaction length gets problematic.

The parameters of an analytical model of the expected value of retransmissions were derived from the measurement results. The parameter values coincide with the statistic properties of the toll transactions used for the test. Therefore this analytic model can be used to investigate the retransmission rate for toll transactions with different statistic properties than used in this test.

Evaluation details and the results of each test run are provided in clause A.4.

Figures 86 and 88 show that the average number of retransmission per toll transaction depends on T_{on} and T_{off}. The straight lines in these figures are the result of a double logarithmic regression analysis later on used to derive the relation between T_{on} and T_{off}.

Figures 87 and 89 show these relation between T_{on} and T_{off} when the number of retransmissions is limited. The red line was derived from the double logarithmic regression analysis shown in figures 86 and 88 under the precondition of an average retransmission rate of one per transaction. The shaded regions determine T_{on} and T_{off} ranges where certain average retransmission rates are expected derived from the analytical model. Taking the limits for T_{on} and T_{off} defined above into account, the required average retransmission rate of less than one can be met for this tested transaction by limiting T_{on} to a maximum of 5 ms and using a time T_{off} of more than 33 ms. For longer transactions (not used in these test runs) this time T_{off} should obviously be increased (to e.g. 50 ms).

Further simulations with the analytical model can also assess whether the same limits apply for toll plazas with much longer transaction durations.

6.3.3.2 Test results for OBU10 (TD_COEX_OBU_02)

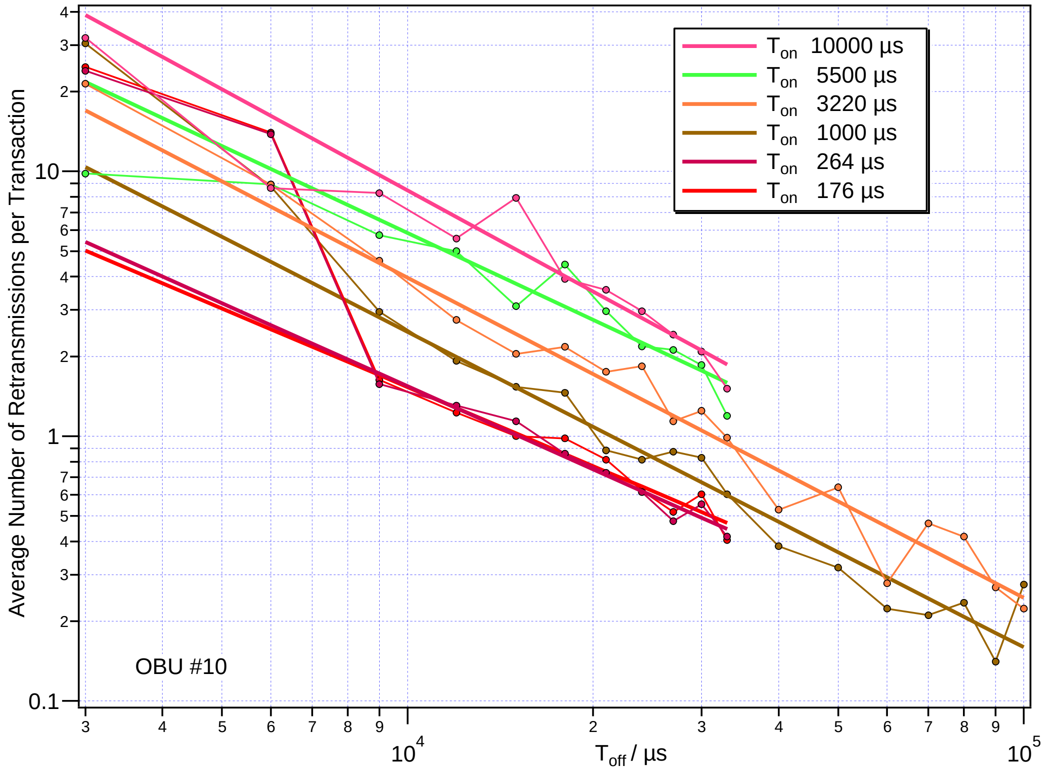


Figure 86: Average number of retransmissions per toll transactions with OBU10, TD_COEX_OBU_02, test runs 1 to 6

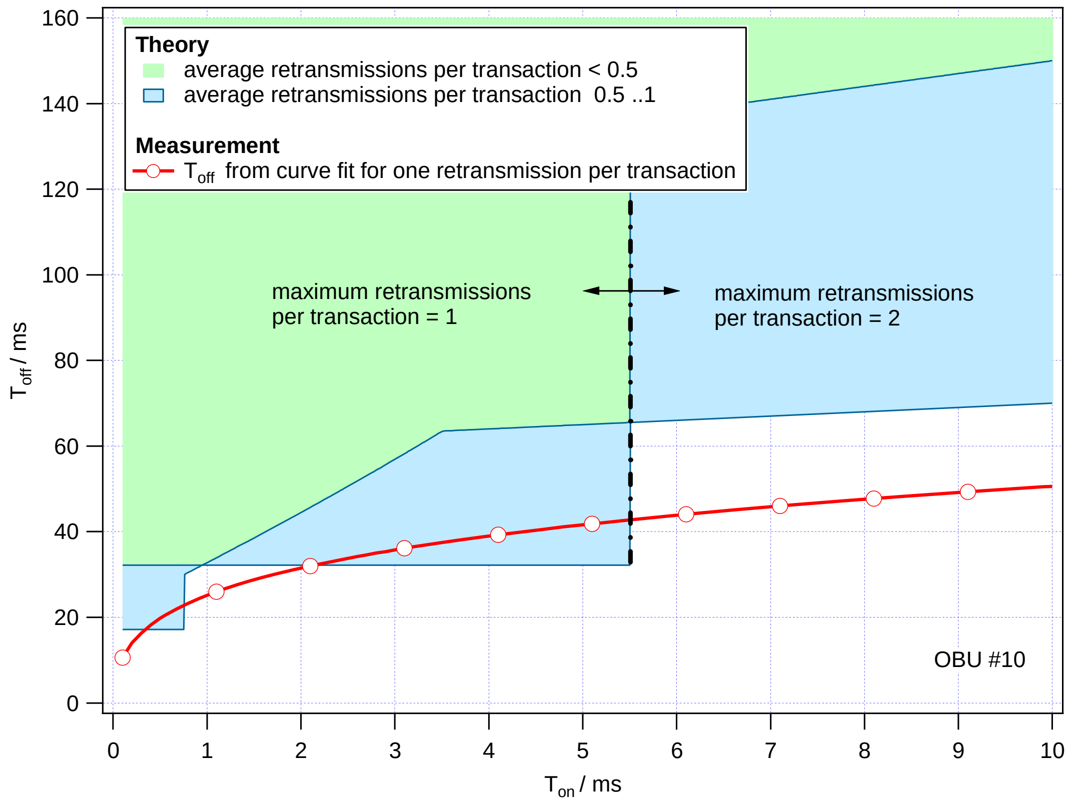


Figure 87: Relation between T_{on} and T_{off} for an expected average retransmission rate for OBU10, TD_COEX_OBU_02, test runs 1 to 6

6.3.3.3 Test results for OBU12 (TD_COEX_OBU_02)

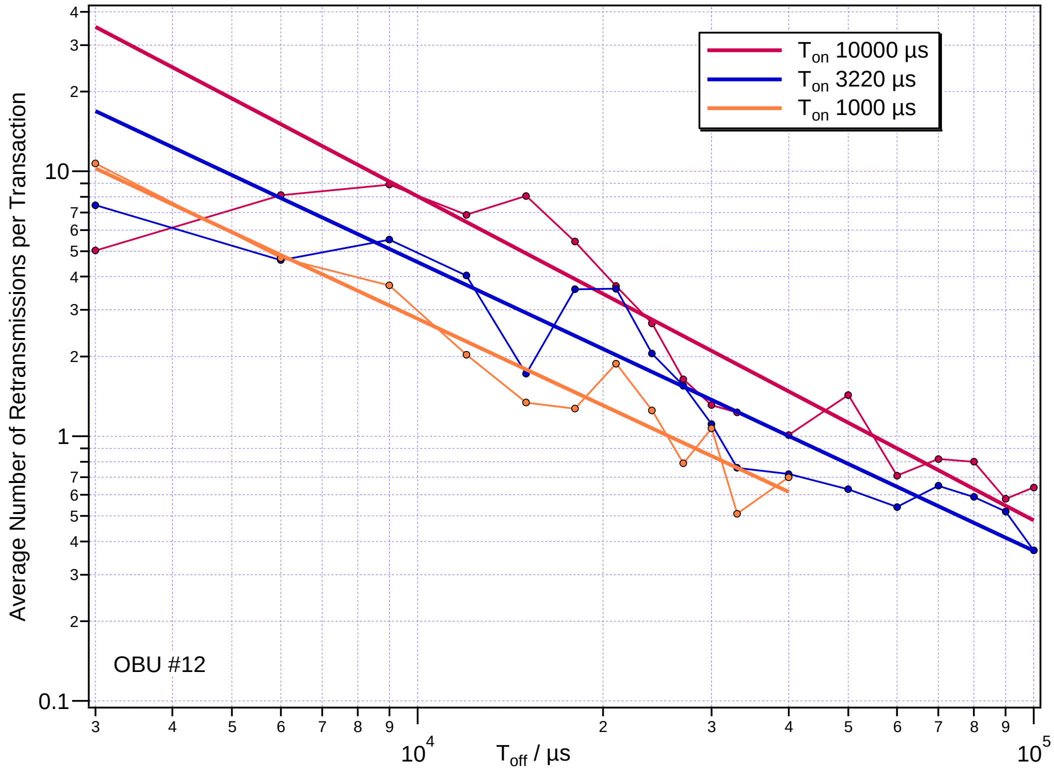


Figure 88: Average number of retransmissions per toll transaction with OBU12, TD_COEX_OBU_02, test runs 7 to 9

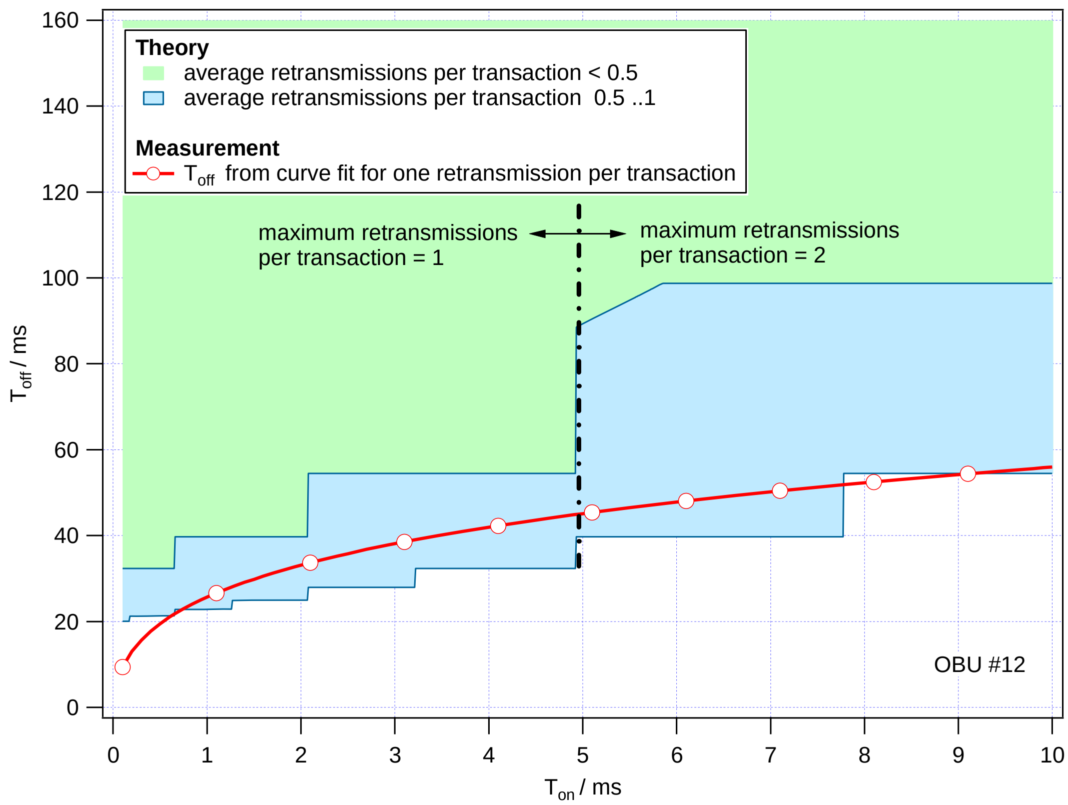


Figure 89: Relation between T_{on} and T_{off} for an expected average retransmission rate for OBU12, TD_COEX_OBU_02, test runs 7 to 9

6.3.4 Measurement 3: Single ITS-G5A Station installed on rooftop

6.3.4.1 Test run and evaluation details

This test was performed and evaluated in the same manner as measurement 2 described in clause 6.3.3.1, except the ITS-G5 antenna was placed on the rooftop of the SUV. In this setup it was expected that also (or even only) interference to the CEN DSRC RSU occurs.

Further details of the test setup and the test runs are listed in table 26. The evaluation details provided in clause A.4 for measurement 2 are also valid for the evaluation of this measurement.

6.3.4.2 Test results for OBU12 (TD_COEX_OBU_03)

Since the OBU and transaction type was the same as used in measurement 2 and described in clause 6.3.3.3 the results can be compared. Figures 88 and 90 show no significant difference. But the model in figure 91 shows that T_{on} should be below 3,6 ms to avoid more than one retransmission per transaction for the setup with the roof mounted ITS-G5 antenna. The fact that this value differs significantly from the 5 ms obtained in measurement 2, could be an indication that the interference mechanism was different for these two setups. But more details of this dissimilarity cannot be deduced from these results.

Results of each test run are provided in clause A.5.

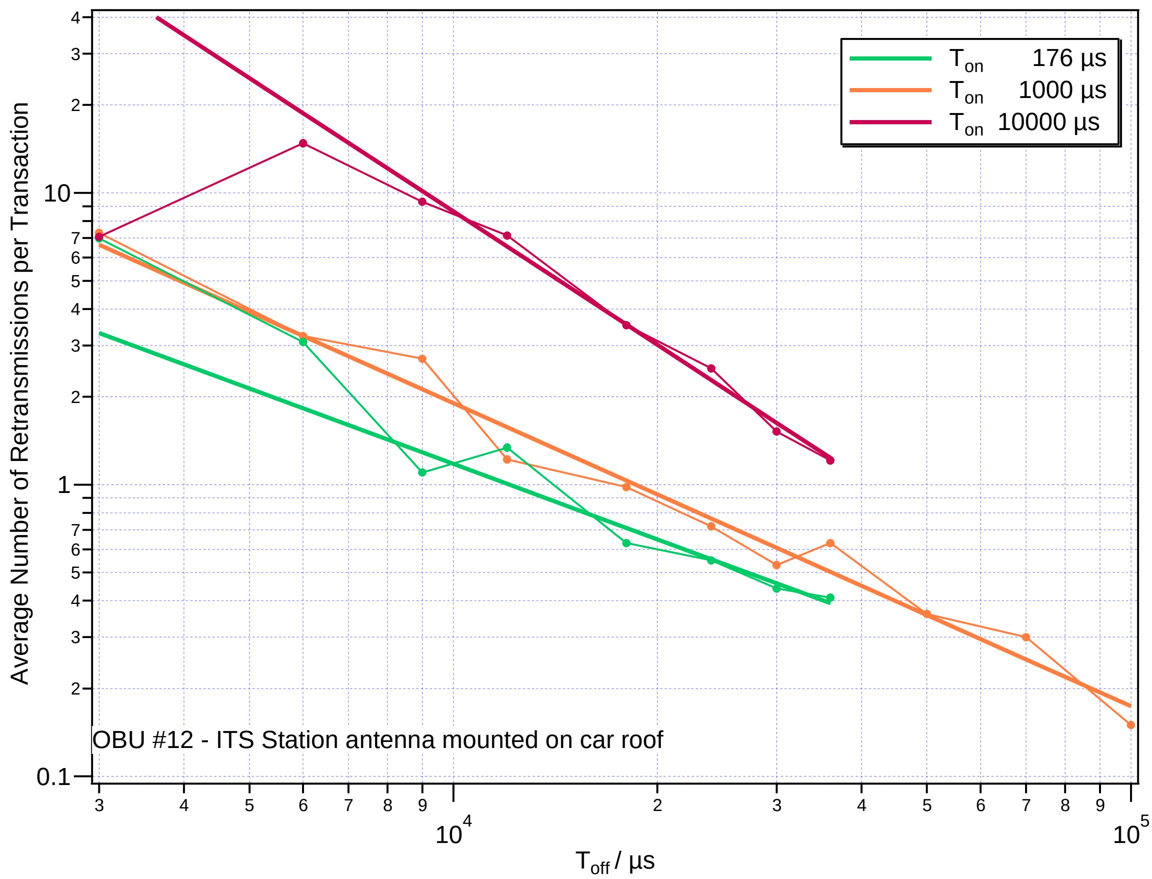


Figure 90: Average number of retransmissions per toll transactions with OBU12, TD_COEX_OBU_03, test runs 2 to 4

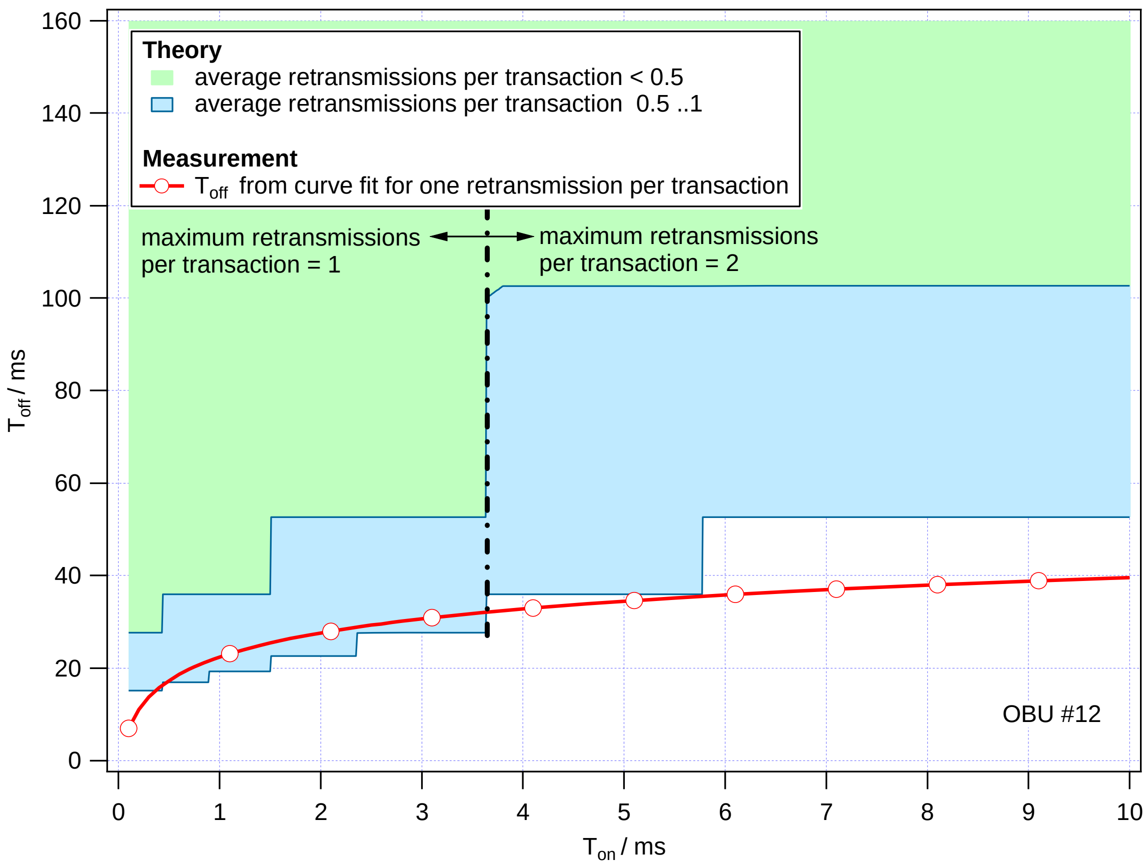


Figure 91: Relation between T_{on} and T_{off} for an expected average retransmission rate for OBU12, TD_COEX_OBU_03, test runs 2 to 4

6.3.5 Measurement 4: Multiple interferer using ITS system emulator

6.3.5.1 Test run and evaluation details

The test runs were performed as described in clause 6.2.7.

The transaction time (duration) was evaluated for several hundred transactions per duty cycle. From these results a probability density function for each duty cycle was estimated.

For the evaluation of the duty cycle effect the BER is not an adequate parameter. The toll transaction duration statistics needs to be evaluated and depending on the ITS-G5 transmit power level only the ITS signals above a given power threshold at the OBU position should be taken into account for the calculation of the interference load.

6.3.5.2 Measurement 4 results

Figure 92 shows the maximum of the probability density function of the transaction time for duty cycles up to 25 %, and the relative increase of the transaction time compared to an undisturbed communication.

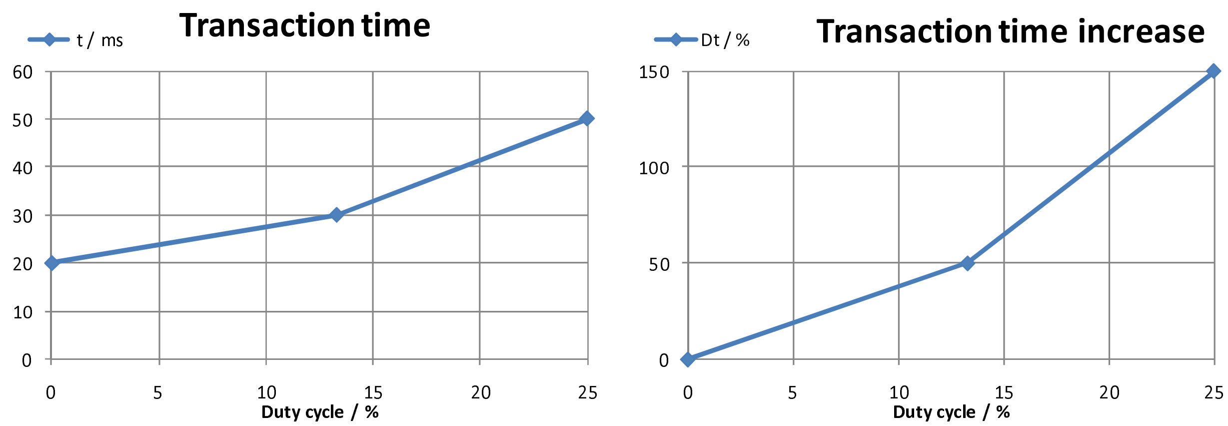


Figure 92: Transaction duration of OBU11 for different ITS-G5 duty cycles

Interestingly, the 66 % duty cycle interference signal caused a transaction time comparable to the 13,3 % duty cycle signal (see figure 93) and is therefore not shown in figure 92. The reason for this is that the 66 % duty cycle signal used 1 000 Byte packets and the T_{off} times in between the frames were longer compared to the other duty cycles which used 200 Byte frames. This caused less CEN DSRC frame retransmissions, since more CEN DSRC frames could be received in these notches correctly. From this result can be concluded that a duty cycle definition by the ratio of the T_{on} and T_{off} time is insufficient to ensure coexistence between CEN DSRC and ITS-G5. The duty cycle should always be defined by absolute values of T_{on} and T_{off}.

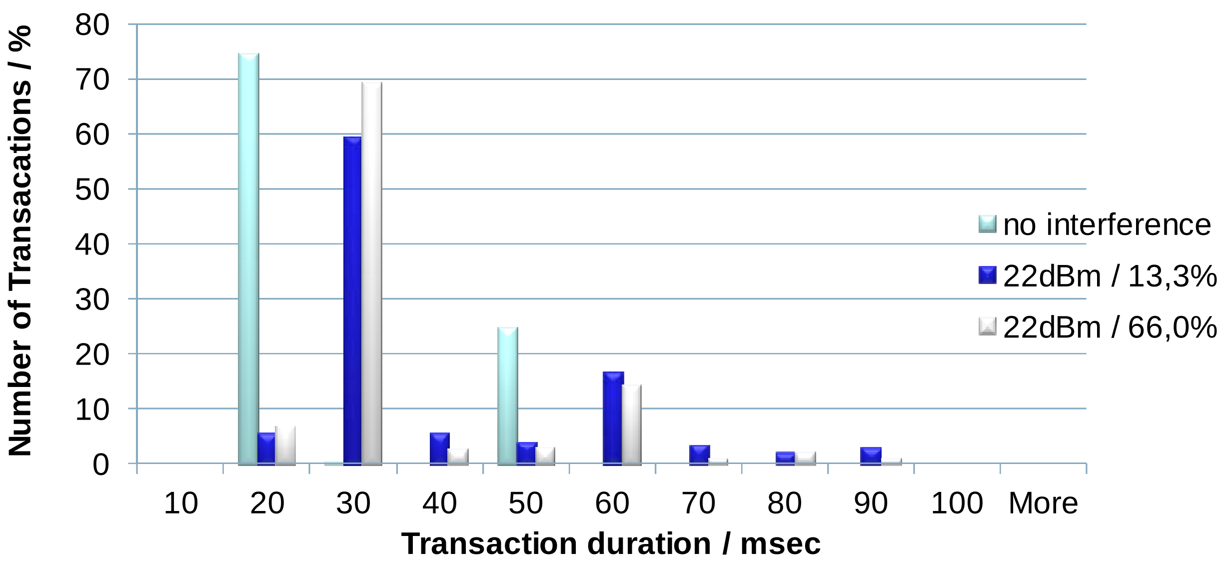


Figure 93: Histogram of the transaction duration of OBU11 for different ITS-G5 duty cycles

6.4 Summary of measurement results

The sensitivity measurement results achieved in measurement 1 are confirming the theoretical sensitivity values assumed in TS 102 792 [i.7] and evaluated in TR 102 654 [i.4]. In addition to the worst case sensitivity limits assumed in TS 102 792 [i.7] and TR 102 654 [i.4] the measurement results lead to directional diagrams of the combined sensitivity pattern.

The results of low duty cycle measurements 2 and 3 show that the ITS antenna position is not relevant for the performance degradation of the CEN DSRC system in those test setups.

During the evaluation of the results it has been discovered that the best evaluation criteria for the performance degradation of the CEN DSRC system under low duty cycle interference from ITS-G5 system is the evaluation of the CEN DSRC frame retransmission rate during a transaction.

Based on the results achieved in all low duty cycle measurements simple coexistence rules based on T_{on} and T_{off} times can be derived. The results described in the present document show that the coexistence rules are not in contradiction with the parameters discussed for DCC and ITS-G5 channel configuration (see [i.8]).

The result of measurement 4 confirms the results achieved in measurement 1, 2 and 3.

7 Conclusions and further steps

7.1 Critical scenarios

Based on the simulation and measurement results critical operational scenarios can be identified.

- Single interferer on rooftop of car equipped with CEN DSRC OBU
- Single interferer in front of car equipped with CEN DSRC OBU
- Single interferer overtaking a car equipped with CEN DSRC OBU

This results in following worst case scenario:

- Several interferers in close vicinity plus interferer on rooftop of the car equipped with a CEN DSRC OBU

7.2 Propose mitigation measures

7.2.1 Conclusions and consequences

All measurements and simulations have shown that a combination of ITS-G5 TX output power level limitation and reduction of the transmission duty cycle can ensure coexistence between ITS-G5 stations and CEN DSRC tolling. For ITS-G5 Stations with an output power level below 10 dBm no additional duty cycle control is necessary. Simulations have shown that the idle time T_{off} where the interfering ITS-G5 stations should not transmit with power levels above 10 dBm is linearly dependent on the number of interfering stations n and the length of the transmission bursts T_{on}.

Since the number of interferers to a CEN DSRC OBU cannot be counted directly, this number can be estimated from the ITS-G5 station density and the transmit power levels. But the transmit power levels are also unknown, so an estimation of them is necessary too.

This estimation problem can be solved differently for the tree possible use cases:

- Burst time T_{on} and range (transmit power level) are given → determination of idle time T_{off}
- Bust time T_{on} and idle time T_{off} are given → determination of maximum range (transmit power level limit)
- Idle time T_{off} and range (transmit power level) are given → determination of bust time T_{on}

7.2.2 Determination of idle time T_{off}

For the determination of T_{off} from the burst time T_{on} and the range (transmit power level) by use of equation 1 the number of interfering ITS stations n is necessary. Under the assumption that all ITS-stations have the same given parameters, n can be estimated from the isolation distance d for the given transmit power level P_{Tx} in dBm and the OBU susceptibility limit $P_{itf\ Limit}$ = -51,6 dBm according to equation 12 (see also [i.7]):

$$d = d_0 \cdot 10^{\frac{PL(d) - PL_0 - \sigma}{10 \cdot n}} \qquad (12)$$

$$PL(d) = P_{Tx} - P_{itf\ Limit}\,. \qquad (13)$$

Where PL_0 = 47,9 dB (free space path loss at 5,9 GHz in d_0 = 1 m distance), d is the isolation distance in meters and the path loss coefficient is n = 1,8. The margin is set to σ = -6 dB, which includes both shadow fading (± 5 dB peak, according to [i.7]) and 1 dB transmitter calibration offsets. The margin accounts for the worst case and is thus subtracted from the path loss value.

The number of interferers n can be estimated by counting all ITS-G5 stations in the station location table that are closer than the isolation distance d.

Putting this number n and the given T_{on} into equation 1 results in the quested idle time T_{off}.

7.2.3 Determination of the transmit power level limit

For the determination of the transmit power level limit from the idle time T_{off} and the burst time T_{on}, first the maximum number of interfering ITS stations n must be evaluated from equation 1. Under the assumption that all ITS-stations have the same given parameters, the transmit power level limit can be determined by counting the number of interferers sorted in ascending distance up to n. From the distance d of the n^{th} interferer the transmit power level limit P_{Tx} can be calculated according to equation 14:

$$P_{Tx} = \min\left\{ PL_0 - P_{itf\ Limit} + n \cdot 10\log_{10}\left(\frac{d}{d_0}\right) + \sigma\ ,\ 33\ dBm \right\} \qquad (14)$$

Where PL_0 = 47,9 dB (free space path loss at 5,9 GHz in d_0 = 1 m distance), d is the isolation distance in meters and the path loss coefficient is n = 1,8. The margin is set to σ = -6 dB, which includes both shadow fading (± 5 dB peak, according to [i.7]) and 1 dB transmitter calibration offsets. The margin accounts for the worst case and is thus subtracted from the path loss value. The OBU susceptibility limit $P_{itf\ Limit}$ = -51,6 dBm (see [i.7]).

The result is limited to the maximum allowed transmit power level P_{Tx} of 33 dBm.

7.2.4 Determination of bust time T_{on}

For the determination of the maximum allowed burst time T_{on} after a known idle period with length T_{off} and a requested minimum range (transmit power level P_{Tx}) by use of equation 1 the number of interfering ITS stations n is necessary. The problem is similar to the one in clause 7.2.2. By use of equation 12 the isolation distance for the given transmit power level can be determined and all ITS-G5 stations within this distance d can be counted in the station location table to get an estimation of n.

Finally equation 1 can be used to determine T_{on} from T_{off} and n. With the restriction that the maximum allowed burst time T_{on} should not exceed 5 ms as already mentioned in clause 5.5.1. This can be done by simply limiting the result.

7.3 Further steps

There are some topics that can be worked on after publication of the present document:

- Implementation of the mitigation methods described in clause 7.2 into a simulation of more complex traffic scenarios to evaluate the proposed estimation methods.
- Simulation of the combination of a DCC with the mitigation methods described in clause 7.2.
- Field testing of the combination of a DCC with the mitigation methods described in clause 7.2.

Annex A:
Detailed Measurement Results

A.1 Introduction

Annex A presents detailed results of the calibration, measurements 1, 2 and 3 including intermediate results used for calculating the final result representations as found clause 6.3 of the present document.

A.2 Calibration

A.2.1 Substitution Antenna Measurements (TD_CAL_01)

A.2.1.1 Test run and evaluation details

The substitution antenna used was the LHCP patch antenna as shown in figure A.1 on the right side.

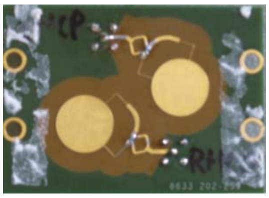


Figure A.1: Substitution antenna used for the calibration measurements

All results of the substitution antenna measurements shown are measured on the antenna connector cable. Do de-embed the power levels at different positions in the test setup, following values can be used:

- Transmit power level P_{TX} = 39 dBm linear polarised
- Distance to OBU:
  - Convertible 10 m - 66 cm = 9,34 m
  - SUV 10 m - 40 cm = 9,6 m
- Free space path loss with PL_0 = 47,9 dB (free space path loss at 5,9 GHz in 1 m distance - see equation A.2)
  - Convertible *PL(*9,34 m*)* = 67,3 dB
  - SUV *PL(*9,6 m*)* = 67,5 dB
  - This difference can be neglected and *PL* can be set to 67,4 dB
- Cable attenuation Att_c = 3 dB
- The linear polarised antenna gain including the windscreen loss *G* can be deduced from the measured power level at 0° azimuth $P_{RX}(0°)$ using equation A.1:
  - The results for $P_{RX}(0°)$ show almost no variation (-35 dBm to -36 dBm) for all test runs.

$$G = P_{RX}(0°) - P_{TX} + PL + Att_c = (-35 .. -36) -39 + 67,4 + 3 = -3,6 .. -4,6 \text{ dBi} \qquad \text{(A.1)}$$

Due to reflections on the metal hull of the vehicle the antenna characteristic is not smooth when rotating it. To distinct between this fading effect caused by the multi path propagation and the major transmission path, a DFT filter was used to generate a curve fit to the local average of the measured values. For the elevation scan the results were mirrored to form a full 360° circle, which leads to a defined edge behaviour (zero slope).

The points where the line of sight was obstructed by the RSU mounting support were excluded from the filtering process to avoid a wrong deviation of the filtered result. The excluded points are marked in figures A.2, A.3, A.4, A.5, A.6 and A.7.

A.2.1.2 Azimuth scan

The azimuth scan for the convertible (figures A.2 and A.3) was done in 7;5° steps. For the SUV measurement (figure A.4), the azimuth step size was reduced to 2,5° to get a better understanding of the fading effect

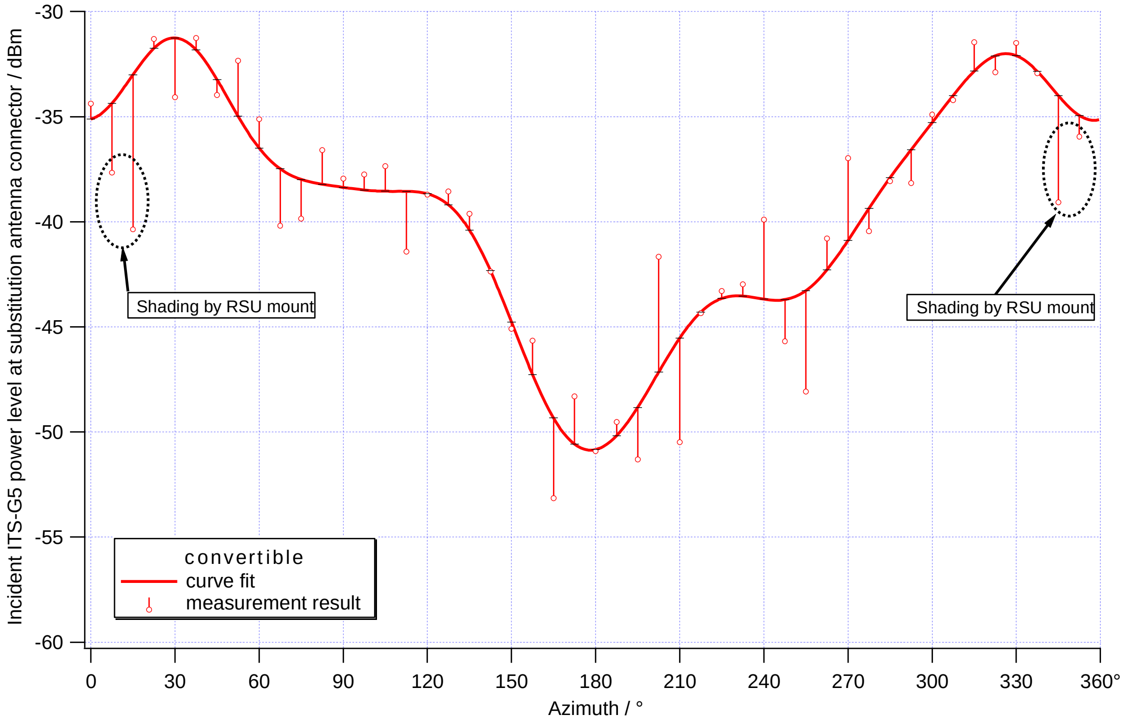


Figure A.2: Power level at cable to substitution antenna for different azimuth angles measured with the antenna behind the wind screen of a passenger car with open roof

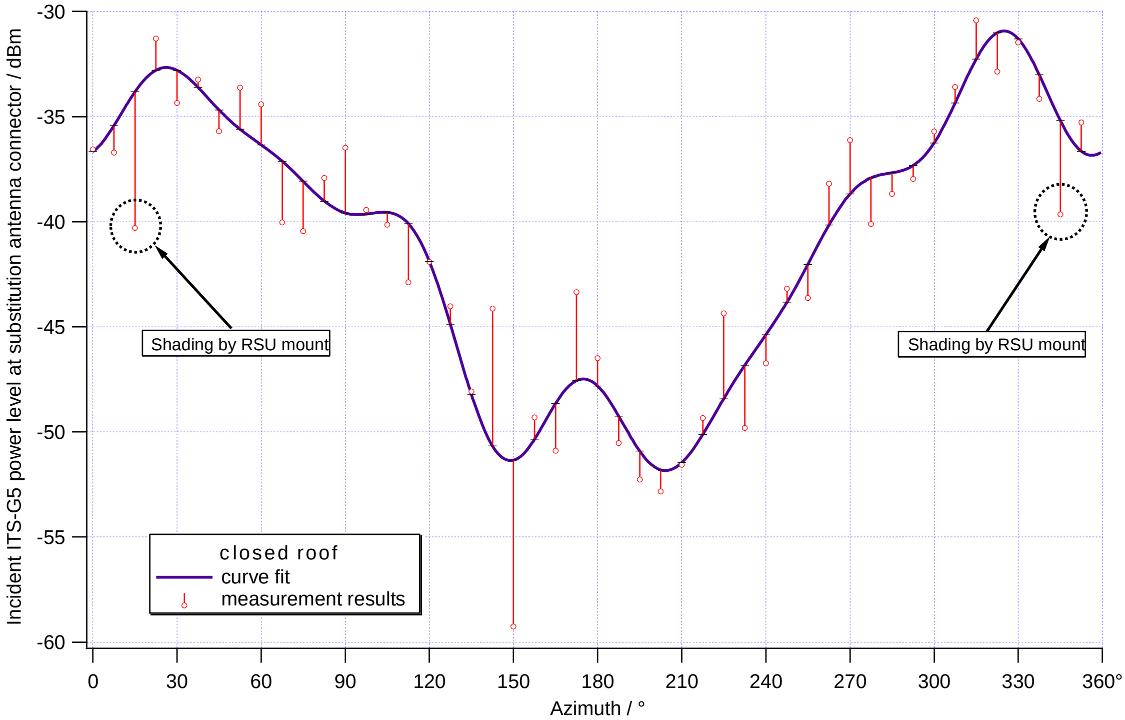


Figure A.3: Power level at cable to substitution antenna for different azimuth angles measured with the antenna behind the wind screen of a passenger car with closed roof

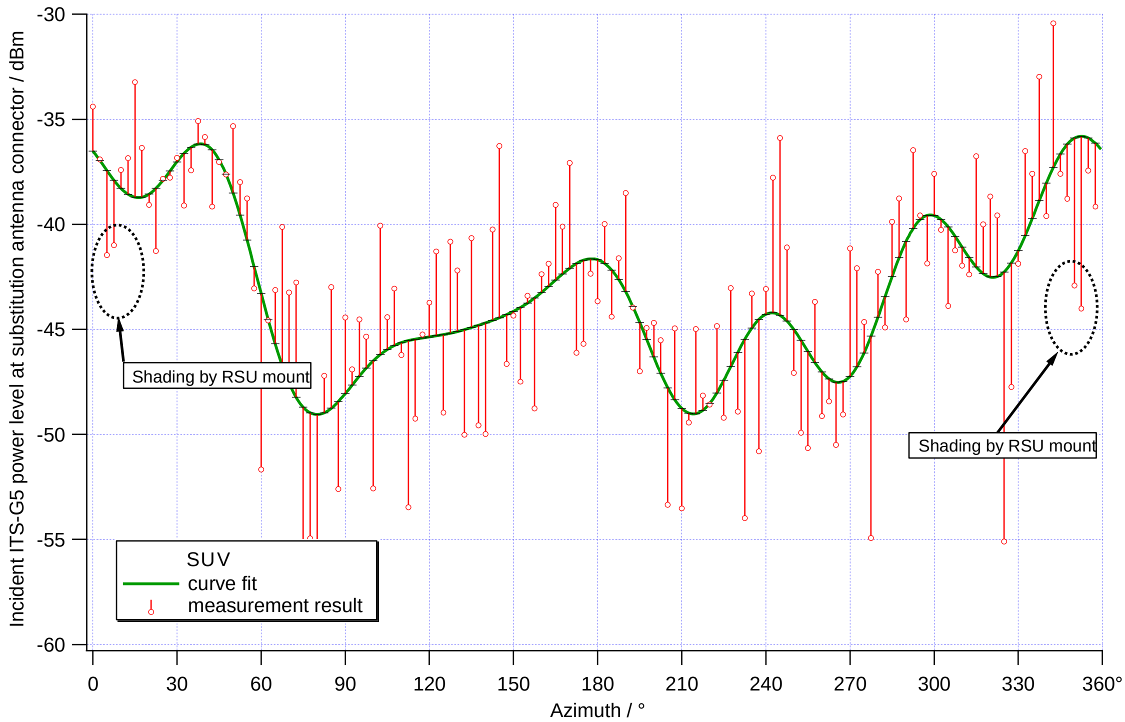


Figure A.4: Power level at cable to substitution antenna for different azimuth angles measured with the antenna behind the wind screen of an SUV

A.2.1.3 Elevation scan

The elevation scan for the convertible (figures A.5 and A.6) was done in 5° steps. For the SUV measurement (figure A.7), the elevation step size was reduced to 2,5° to get a better understanding of the fading effect.

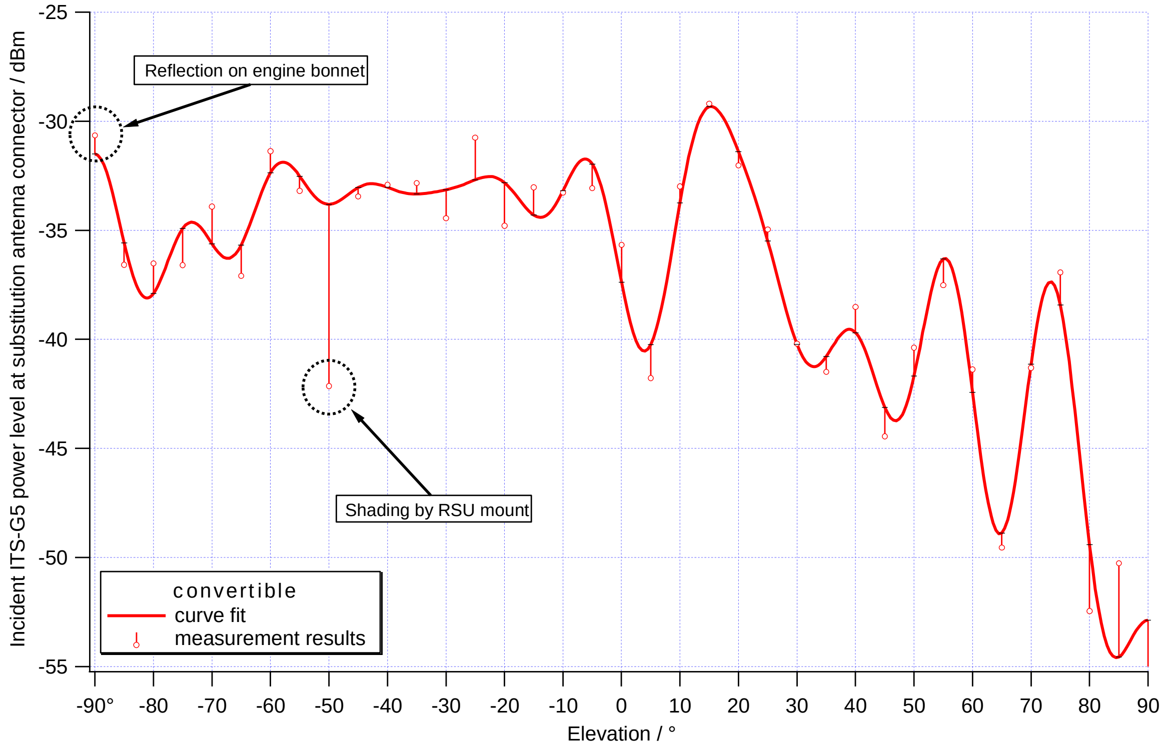


Figure A.5: Power level at cable to substitution antenna for different elevation angles measured with the antenna behind the wind screen of a passenger car with open roof

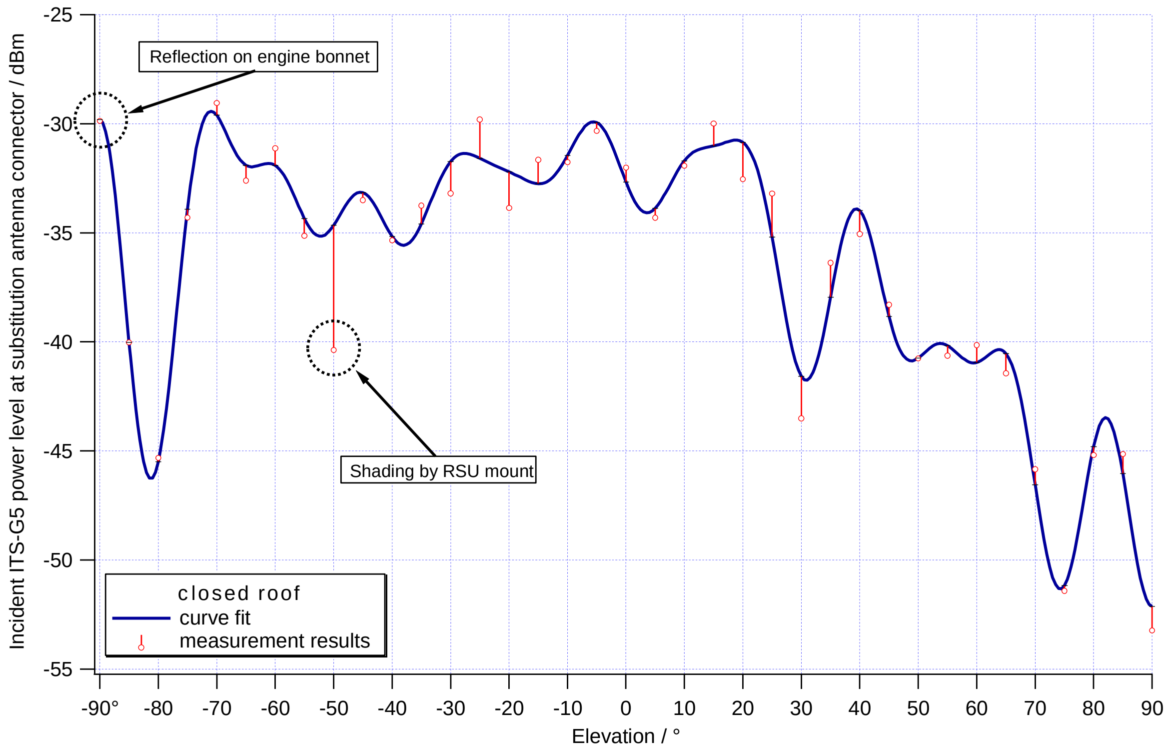


Figure A.6: Power level at cable to substitution antenna for different elevation angles measured with the antenna behind the wind screen of a passenger car with closed roof

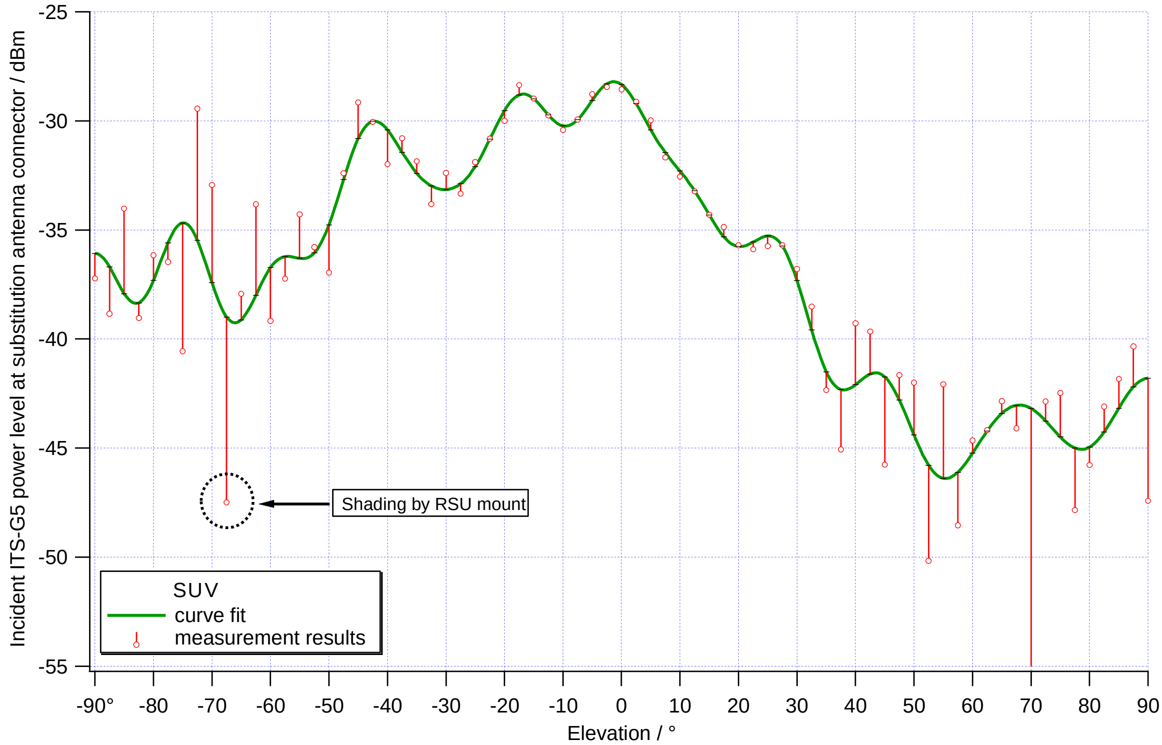


Figure A.7: Power level at cable to substitution antenna for different elevation angles measured with the antenna behind the wind screen of an SUV

A.2.2 CEN DSRC power level at OBU position (TD_CAL_02)

Due to the adaptation of the calibration test plan the calibration measurement TD_CAL_02 has not been performed as planned in the original test plan.

A.2.3 CEN DSRC BER for interferer from the front (TD_CAL_03)

A.2.3.1 Test run and evaluation details

The test was performed by setting the CEN DSRC RSU to a fixed power level that guaranteed a stable communication with a CEN DSRC OBU at CEN DSRC channel 4 with a centre frequency of 5;8125 GHz. An interfering ITS-G5 signal with a centre frequency of 5,88 GHz, transmitted from the front into the OBU, with 100 % duty cycle was used to disturb this communication. The power level of the interferer was swept and the BER of the CEN DSRC link was recorded.

The BER measurement was done by 1 000 ECHO commands with 128 byte length each. The smallest non zero BER that can be determined with this setup is $9{,}8 \times 10^{-7}$ the biggest determinable BER smaller than one is $9{,}8 \times 10^{-4}$. This range allows to measure the BER of 10^{-5} used for determining the interference power limit with a reasonable effort.

To get the interfering ITS-G5 power level P_{itf} in front of the windscreen from the transmitted power level P_{ITS}, the free space path loss model shown in equation A.2 is used.

$$PL(d) = PL_0 + n \cdot 10\log_{10}\left(\frac{d}{d_0}\right) \qquad \text{(A.2)}$$

Where PL_0 = 47,9 dB (free space path loss at 5,9 GHz in 1 m distance), d is the distance in meters, n = 2, and d_0 = 1 m.

The distance d is either 9,34 m for the convertible, or 9,6 m for the SUV test setup.

This results in following free space path losses:

- Convertible *PL*(9,34 m) = 67,3 dB
- SUV *PL*(9,6 m) = 67,5 dB

$$P_{itf} = P_{\mathrm{ITS}} - PL(\mathrm{d}) \quad \text{(A.3)}$$

A.2.3.2 BER evaluation

To find the ITS-G5 transmit power level P_{ITS} that caused a reduced CEN DSRC BER of 10^{-5}, a linear regression was used. For this regression only non saturated BER values were taken into account.

The regression lines are shown in figures A.8 to A.13. The result of the regression analysis is shown in table A.1 together with the calculation of the interference power levels P_{itf} in front of the windscreen.

Table A.1: Evaluation of interference power levels

OBU type	Veh. type	P_{ITS} dBm	*d* m	*PL*(d) dB	P_{itf} dBm
OBU11	car	24,3	9,34	67,3	-43,0
OBU2	car	25,4	9,34	67,3	-41,9
OBU10	SUV	19,7	9,6	67,5	-47,8
OBU12	SUV	14,4	9,6	67,5	-53,1
OBU6	SUV	14,2	9,6	67,5	-53,3
OBU9	SUV	13	9,6	67,5	-54,5
NOTE: OBU6 shows a strange relation between the interference power level and the BER. There are two slops with a minimum in between.					

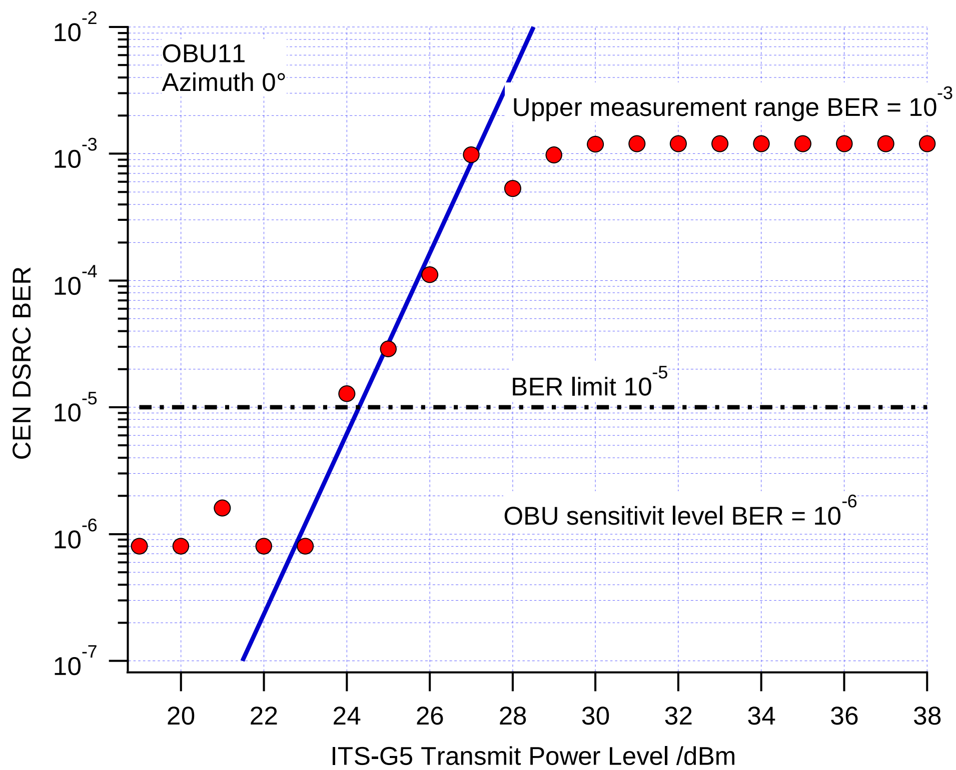


Figure A.8: CEN DSRC BER for an ITS-G5 interferer from the front to OBU11 mounted in a passenger car at a CEN DSRC power setting of 21 dBm

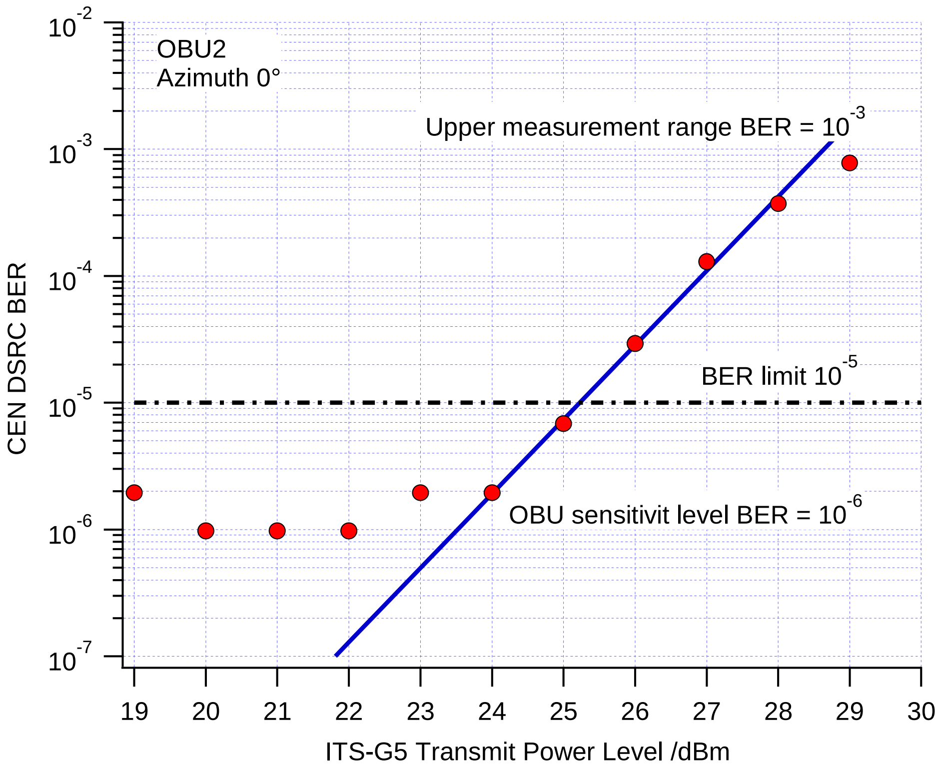


Figure A.9: CEN DSRC BER for an ITS-G5 interferer from the front to OBU2 mounted in a passenger car at a CEN DSRC power setting of 22 dBm

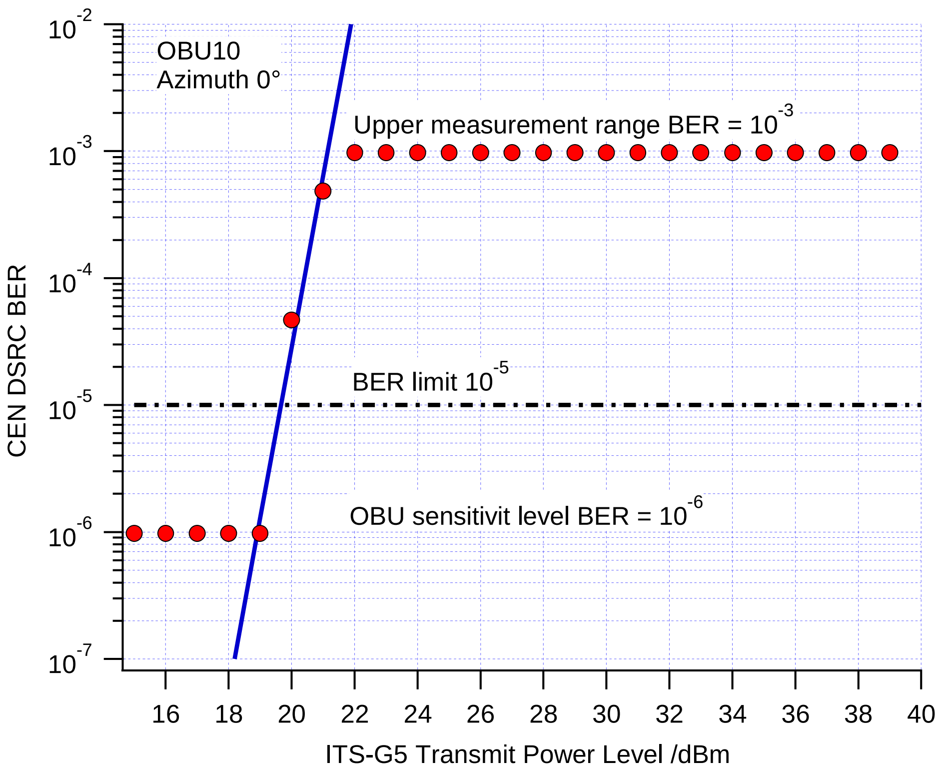


Figure A.10: CEN DSRC BER for an ITS-G5 interferer from the front to OBU10 mounted in an SUV at a CEN DSRC power setting of 26 dBm

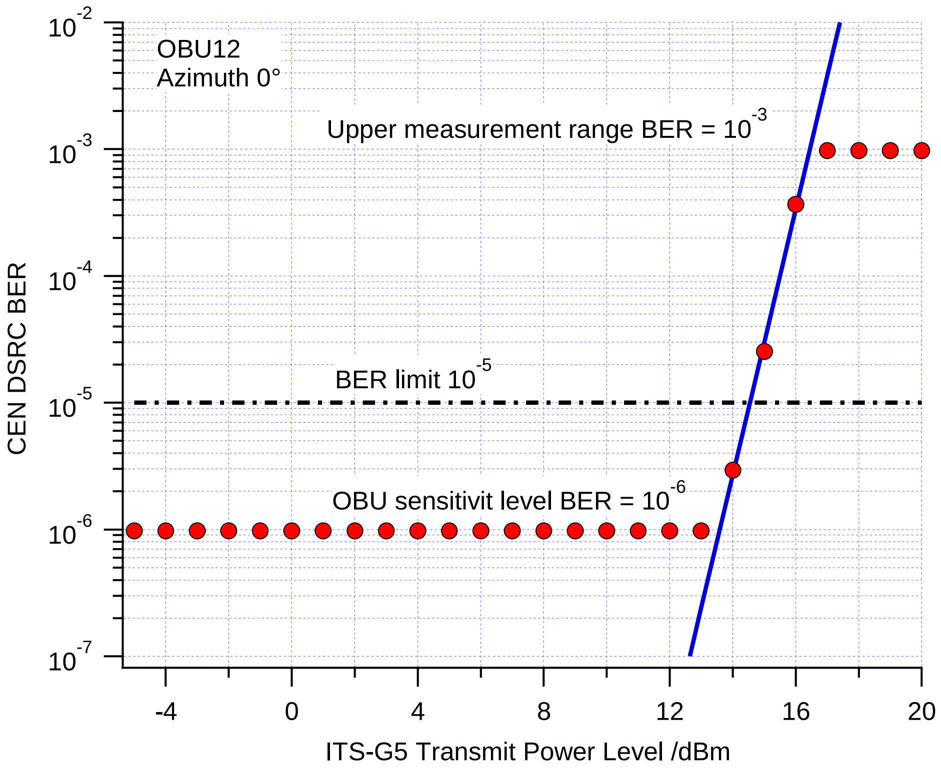


Figure A.11: CEN DSRC BER for an ITS-G5 interferer from the front to OBU12 mounted in an SUV at a CEN DSRC power setting of 23 dBm

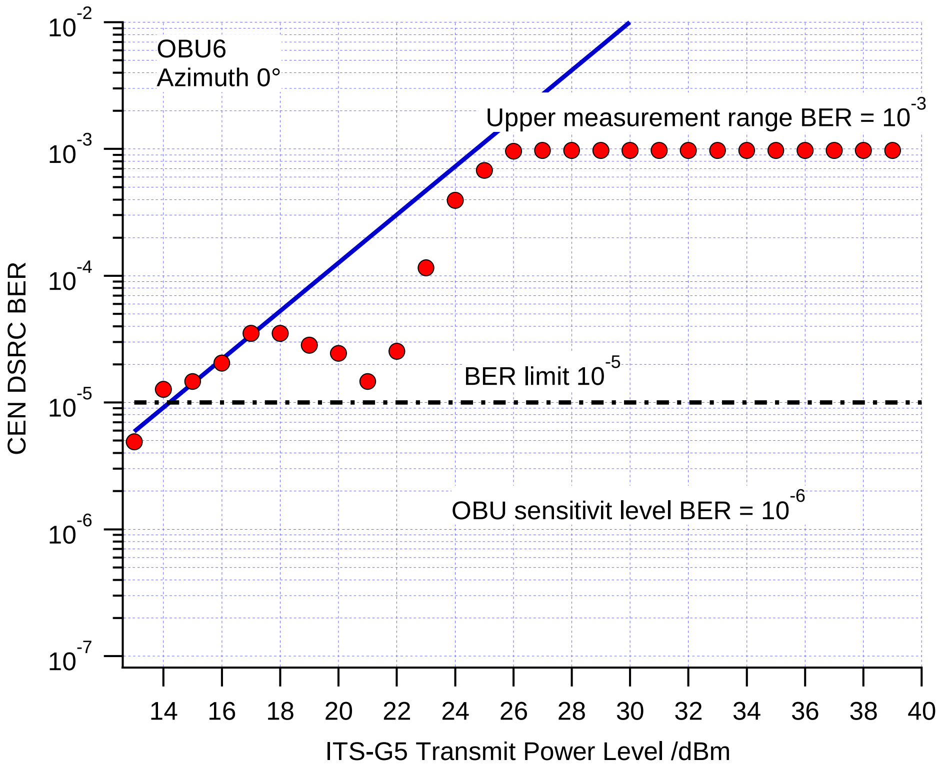


Figure A.12: CEN DSRC BER for an ITS-G5 interferer from the front to OBU6 mounted in an SUV at a CEN DSRC power setting of 23 dBm

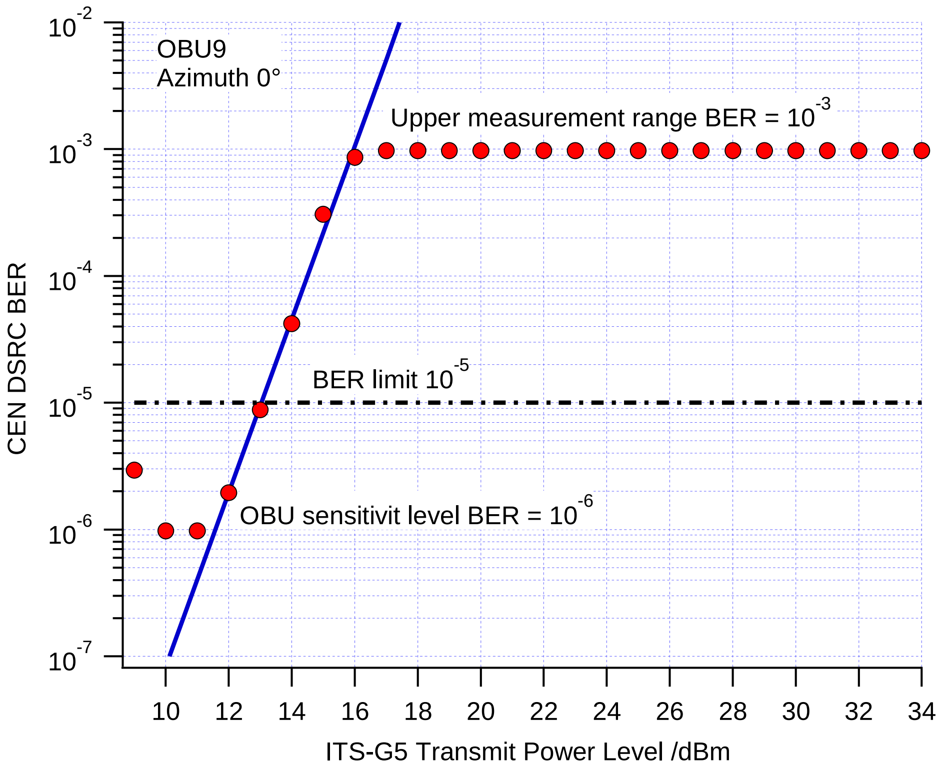


Figure A.13: CEN DSRC BER for an ITS-G5 interferer from the front to OBU9 mounted in an SUV at a CEN DSRC power setting of 23 dBm

A.3 Measurement 1: OBU Interference susceptibility pattern

A.3.1 Test run and evaluation details

The evaluation procedure described in clause A.2.3 was applied to the ITS-G5 TX power sweep of every measured azimuth value. First the ITS-G5 transmit power level for a CEN DSRC BER of 10^{-5} (and 10^{-4}) was evaluated by a linear regression. Than the corresponding power level at the windscreen was calculated by use of equation A.2 with the path loss coefficient $n = 2$.

A DFT filter was used to generate a curve fit to the local average of the interference power limit values. When necessary, the results were mirrored to form a full 360° circle, which leads to a defined edge behaviour (zero slope).

The points where the line of sight was obstructed by the RSU mounting support were excluded from the filtering process to avoid a wrong deviation of the filtered result. The excluded points are marked in figures A.15, A.17, A.19, A.21, A.23 and A.25.

The fading margins were estimated by statistic methods and a DFT filter was used to generate a curve fit to these margins. If too less points for a statistic analysis were available, the fading region was roughly estimated according to the statistics of a similar test run.

Figures A.14, A.16, A.18, A.20, A.22 and A.24 show colour coded the BER for each azimuth and ITS-G5 TX power value. The lines show the evaluated TX power values for a BER of 10^{-5} and 10^{-4} respectively.

The triangles in figures A.14 to A.25 show at which azimuth values the ITS-G5 TX power range was exceeded. No exact interference power limits can be evaluated at these points.

A.3.2 OBU sensitivity evaluation measurement (TD_COEX_OBU_01)

A.3.2.1 TD_COEX_OBU_01: Test run 1

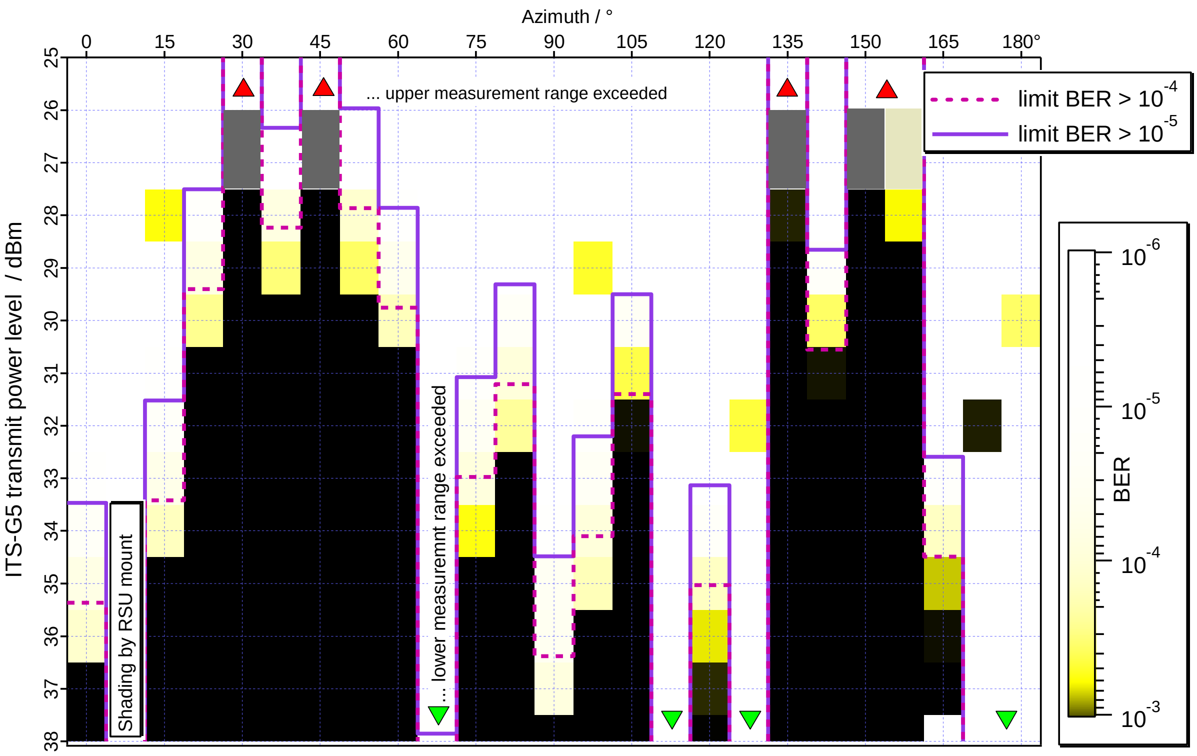


Figure A.14: OBU11 at 6 dB above sensitivity limit (DSRC incident power level -47,2 dBm), raw BER data and evaluated TX power limits, TD_COEX_OBU_01, test run 1

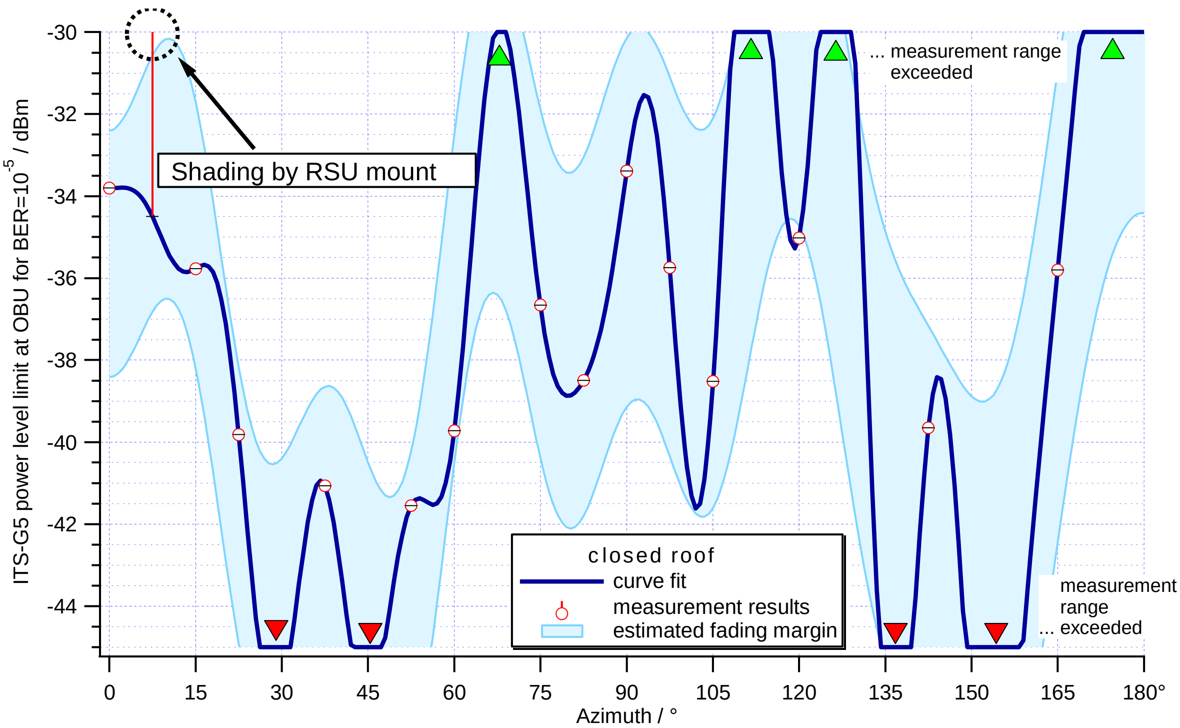


Figure A.15: OBU11 at 6 dB above sensitivity limit (DSRC incident power level -47,2 dBm), de-embedded ITS-G5 power limit of OBU at BER = 10^{-5}, TD_COEX_OBU_01, test run 1

A.3.2.2 TD_COEX_OBU_01: Test run 2

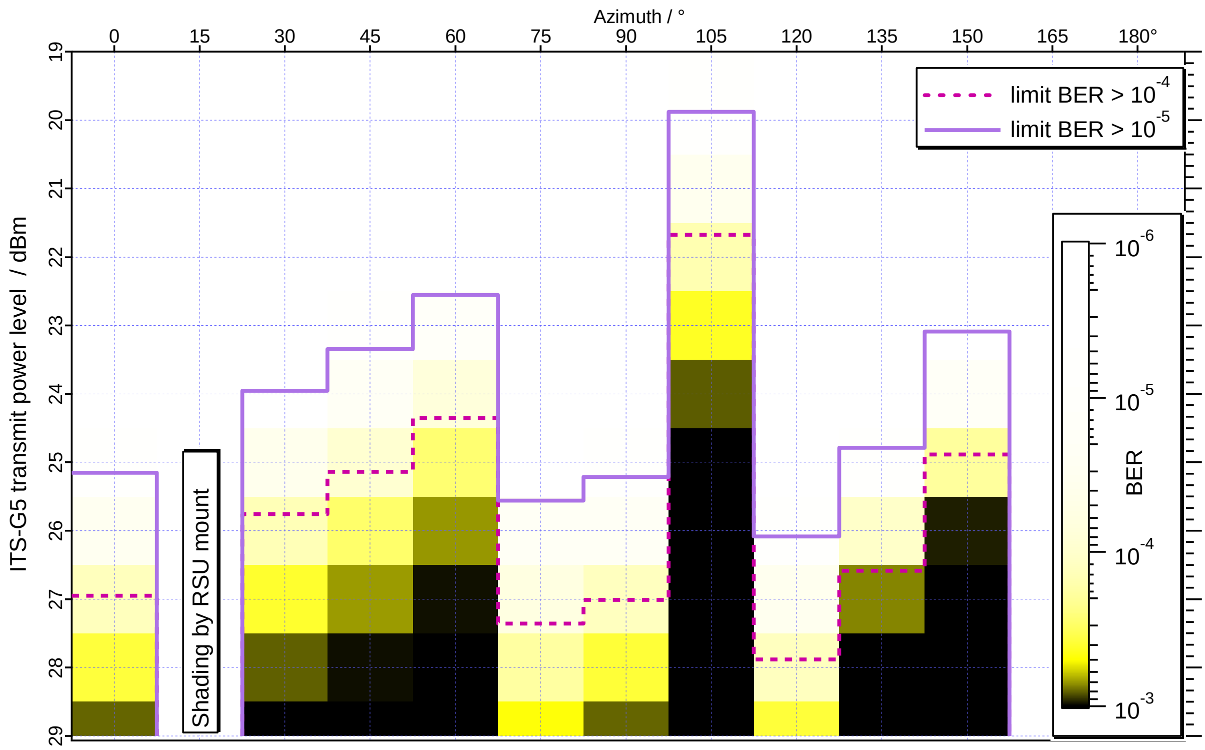


Figure A.16: OBU2 at sensitivity limit (DSRC incident power level -46 dBm), raw BER data, TD_COEX_OBU_01, test run 2

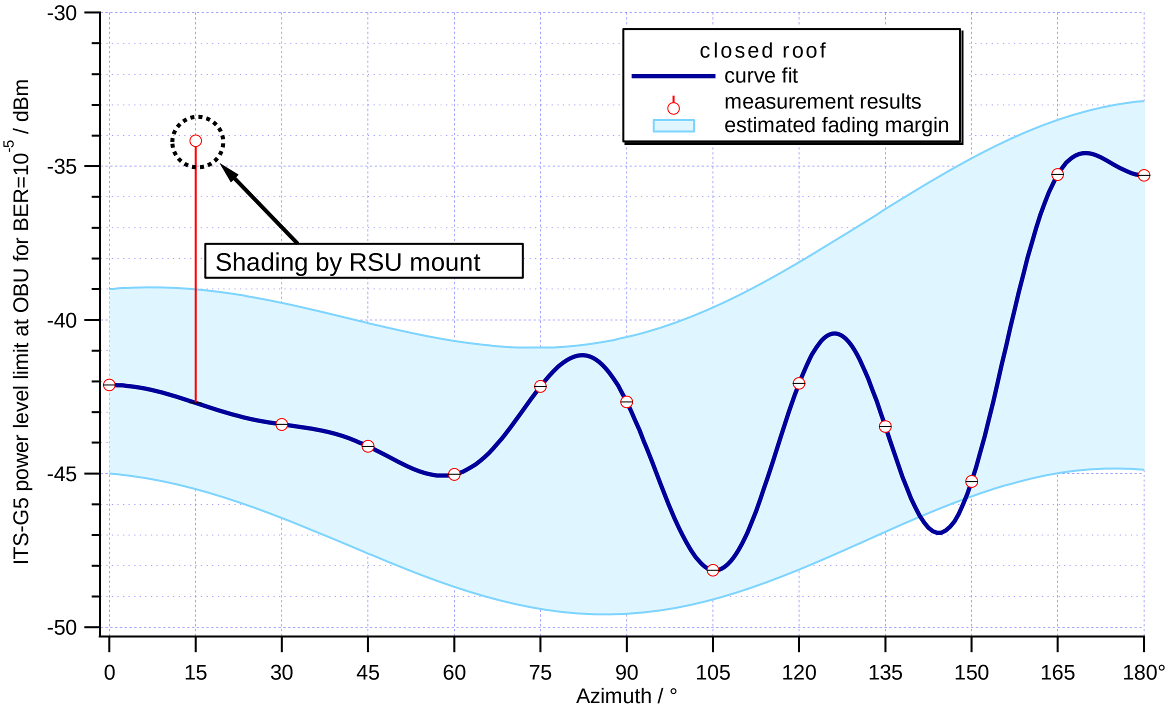


Figure A.17: OBU2 sensitivity limit (DSRC incident power level -46 dBm), de-embedded ITS-G5 power limit of OBU at BER = 10^{-5}, TD_COEX_OBU_01, test run 2

A.3.2.3 TD_COEX_OBU_01: Test run 3

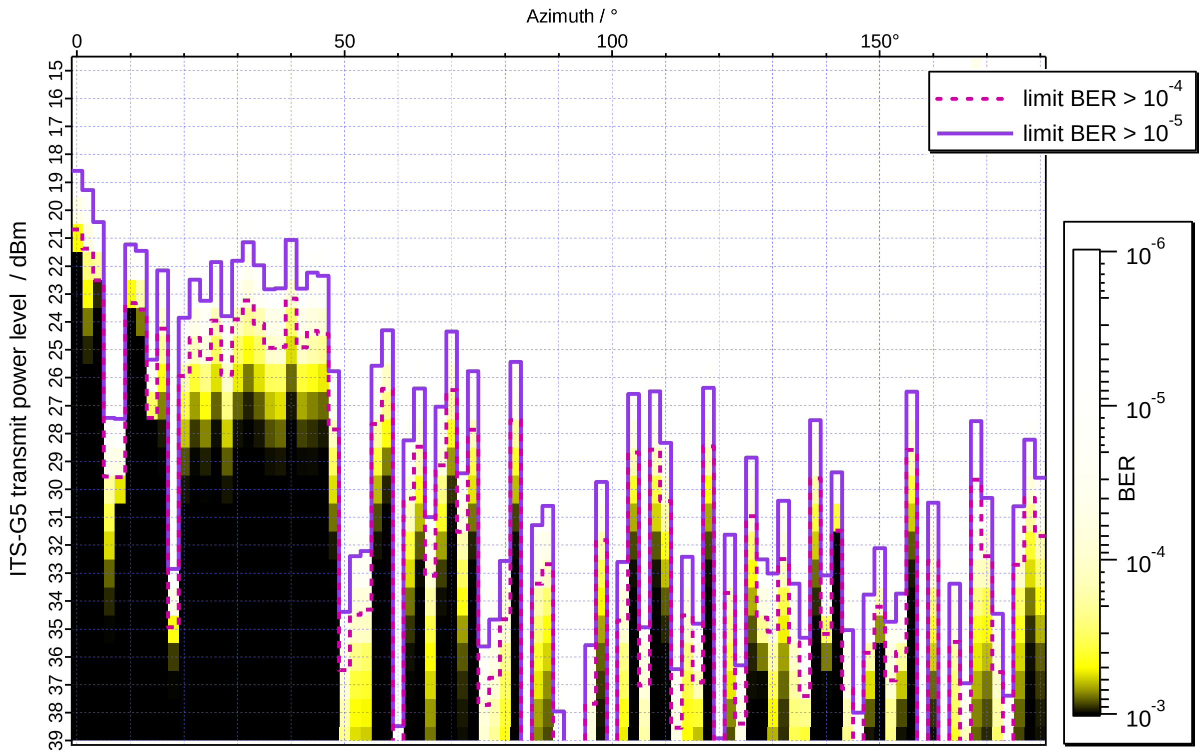


Figure A.18: OBU10 at sensitivity limit (DSRC incident power level -45,2 dBm), raw BER data, TD_COEX_OBU_01, test run 3

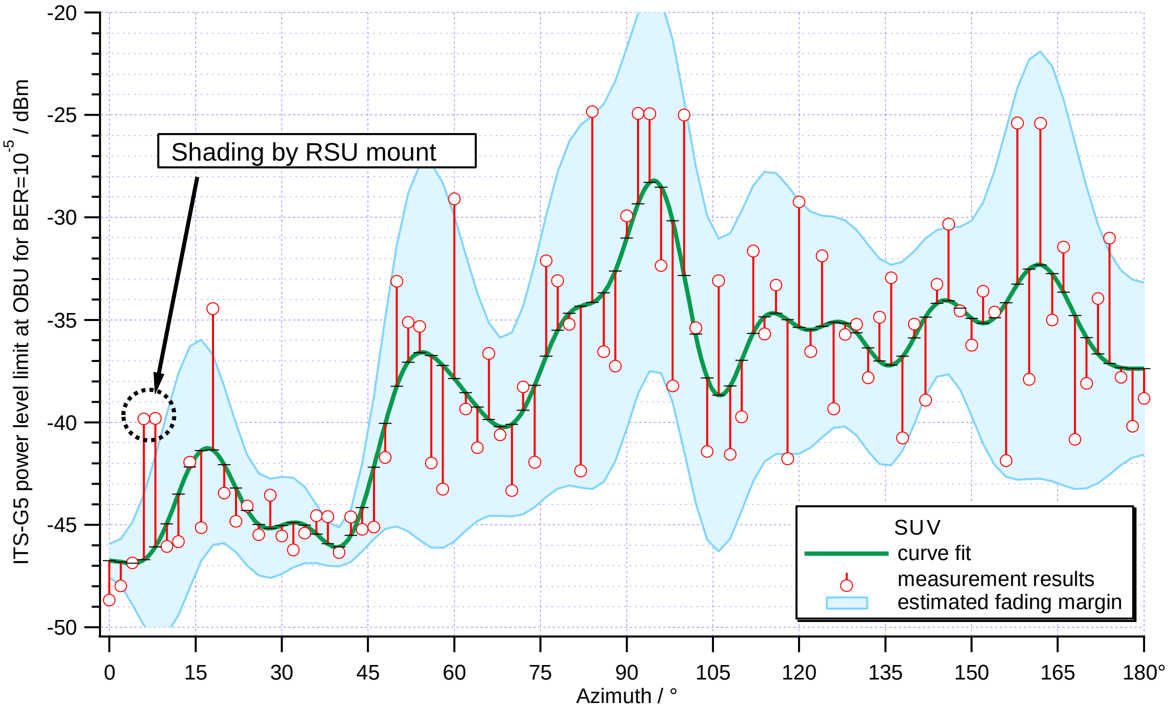


Figure A.19: OBU10 sensitivity limit (DSRC incident power level -45,2 dBm), de-embedded ITS-G5 power limit of OBU at BER = 10^{-5}, TD_COEX_OBU_01, test run 3

A.3.2.4 TD_COEX_OBU_01: Test run 4

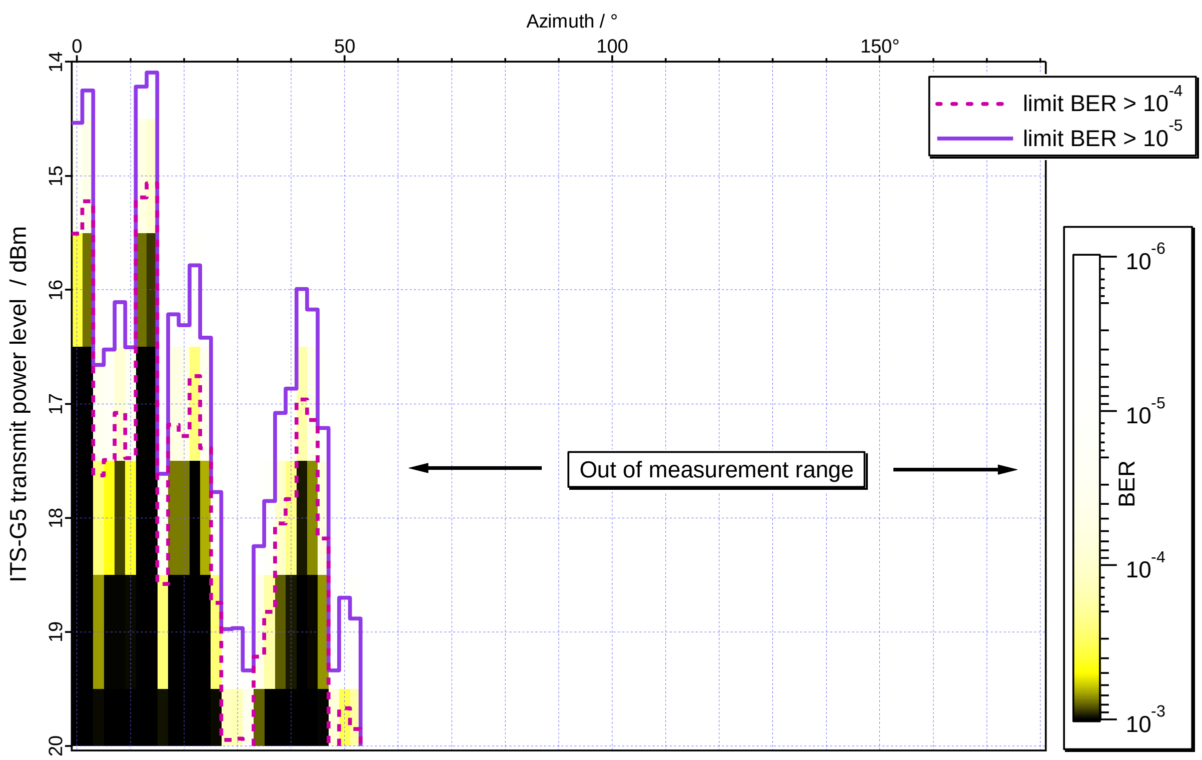


Figure A.20: OBU12 at sensitivity limit (DSRC incident power level -49,2 dBm), raw BER data, TD_COEX_OBU_01, test run 4

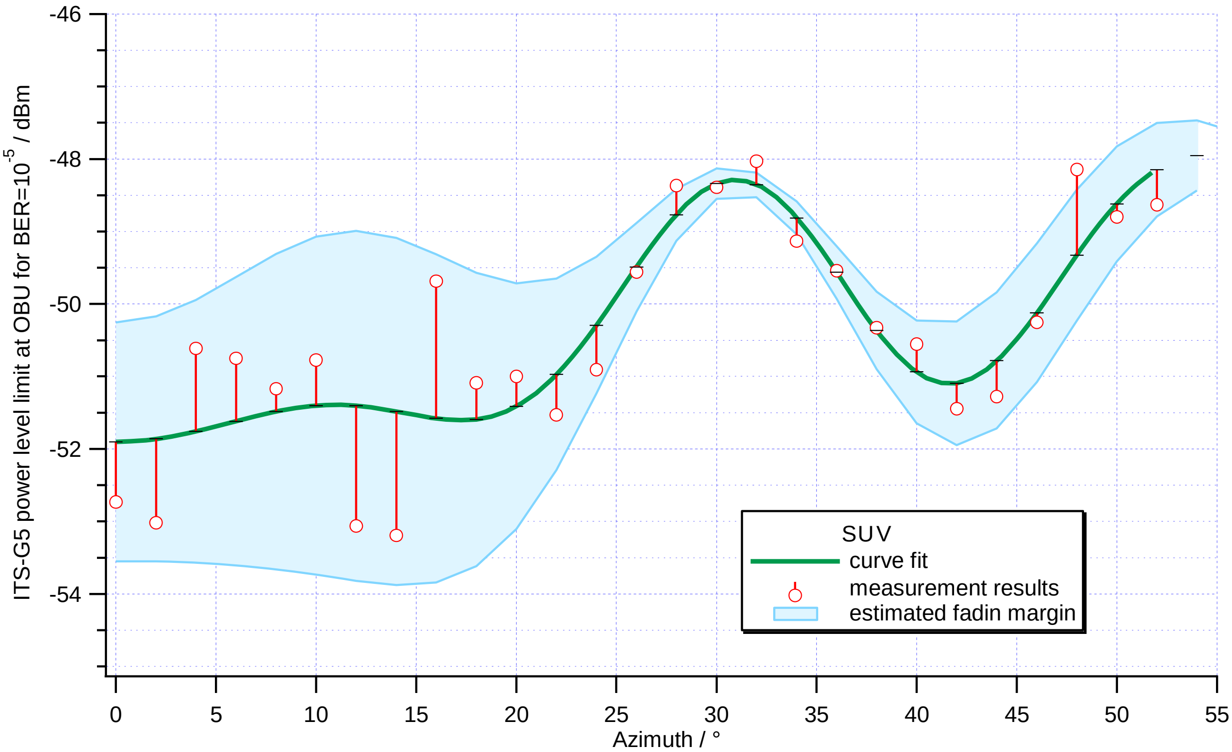


Figure A.21: OBU12 sensitivity limit (DSRC incident power level -49,2 dBm), de-embedded ITS-G5 power limit of OBU at BER = 10^{-5}, TD_COEX_OBU_01, test run 4

A.3.2.5 TD_COEX_OBU_01: Test run 5

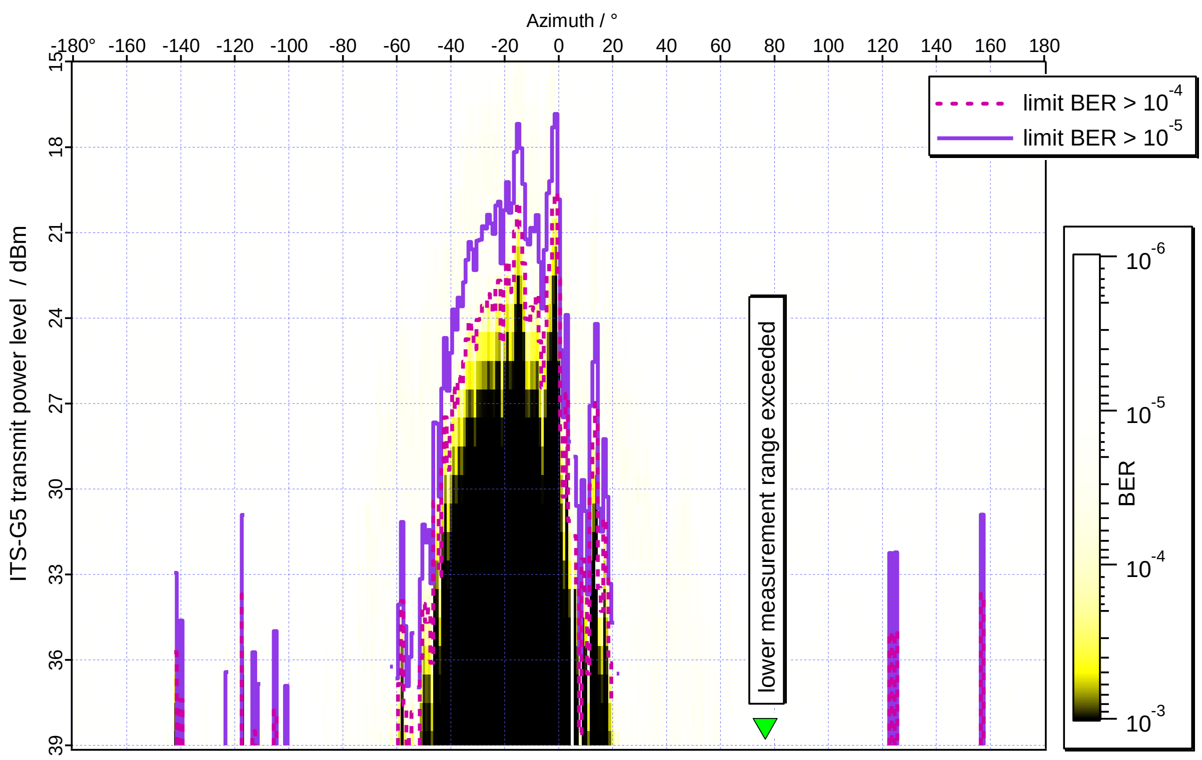


Figure A.22: OBU6 at sensitivity limit (DSRC incident power level -49,2 dBm), raw BER data, TD_COEX_OBU_01, test run 5

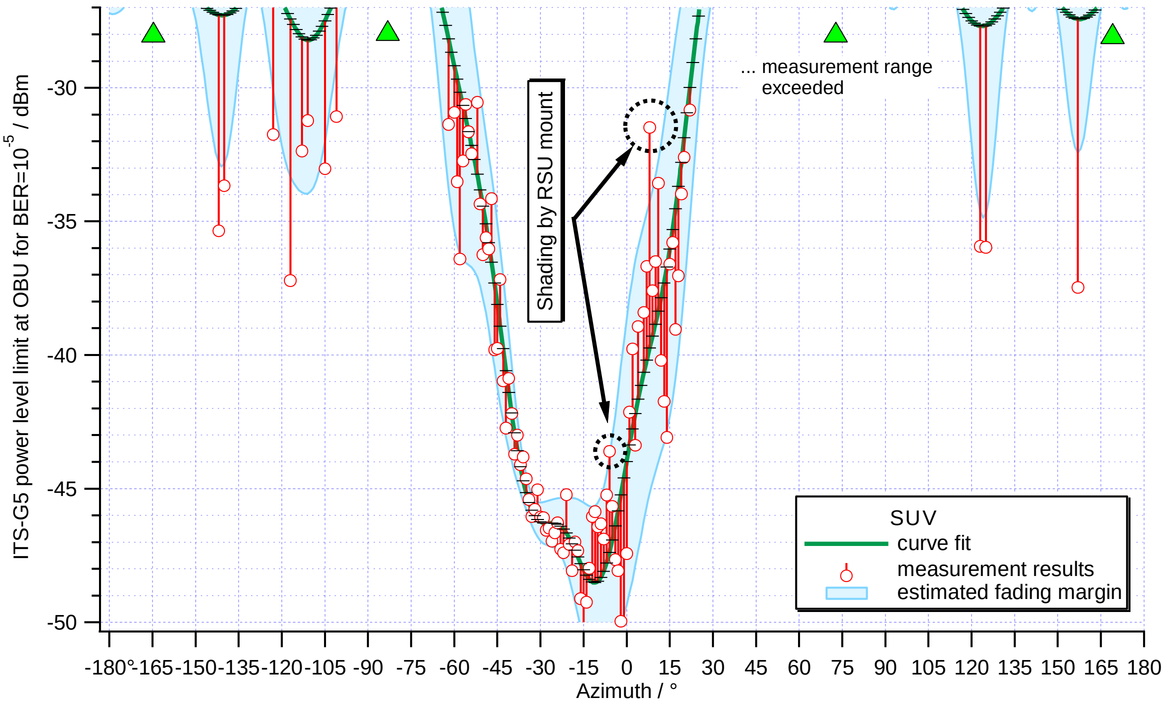


Figure A.23: OBU6 sensitivity limit (DSRC incident power level -49,2 dBm), de-embedded ITS-G5 power limit of OBU at BER = 10^{-5}, TD_COEX_OBU_01, test run 5

A.3.2.6 TD_COEX_OBU_01: Test run 6

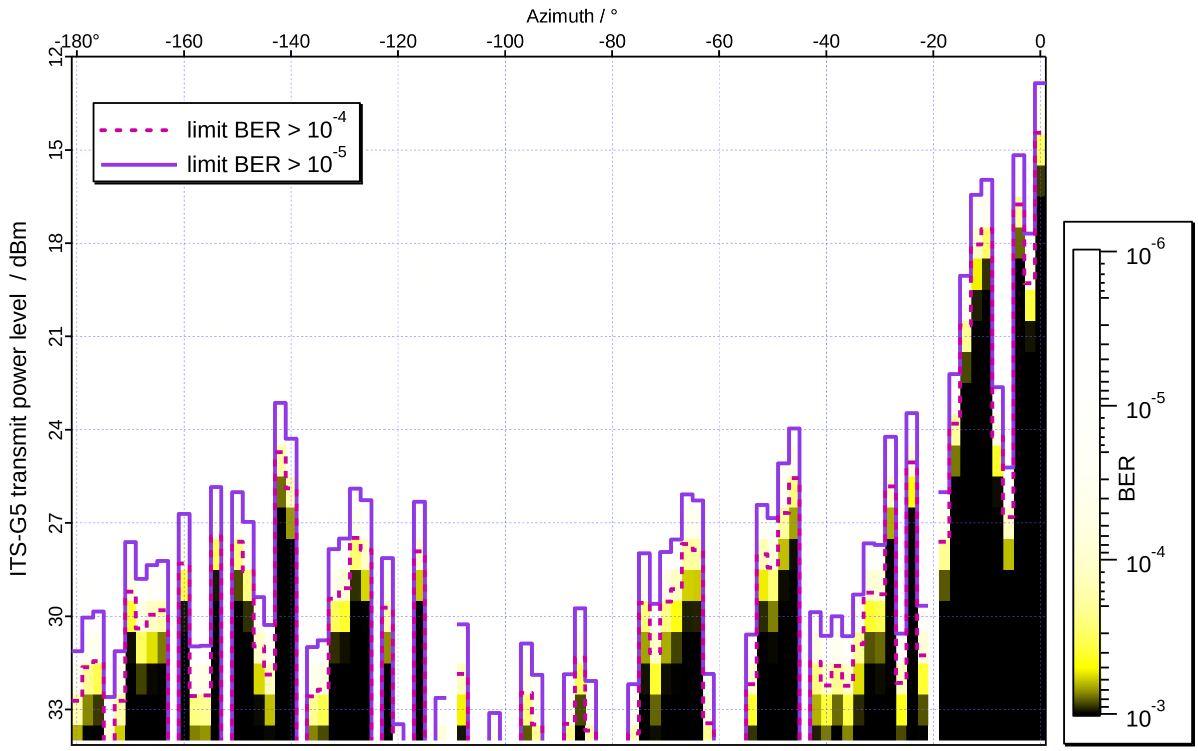


Figure A.24: OBU9 at sensitivity limit (DSRC incident power level -49,2 dBm), raw BER data, TD_COEX_OBU_01, test run 6

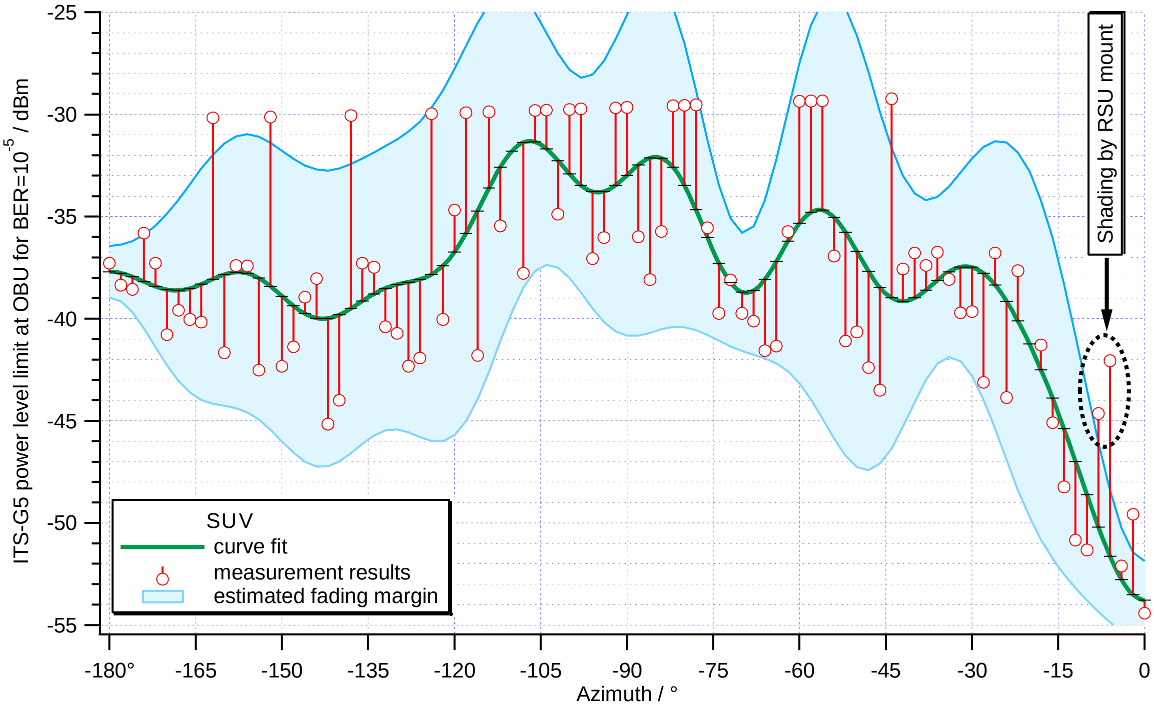


Figure A.25: OBU9 sensitivity limit (DSRC incident power level -49,2 dBm), de-embedded ITS-G5 power limit of OBU at BER = 10^{-5}, TD_COEX_OBU_01, test run 6

A.4 Measurement 2

A.4.1 Statistic evaluation of the test results

Following figures show the statistic properties of the retransmissions and the transaction duration.

The figures include the mean value plus / minus one standard deviation, the minimum and maximum values and the highest peak in the probability density function.

For the mean number of retransmissions per toll transaction an individual two parameter double logarithmic curve fit is shown in each figure. By modelling these parameters as function of T_{on} a multi dimensional empiric model was derived from the test results that could be used to calculate the relation between the retransmission rate, T_{on} and T_{off}.

The four parameter analytic model was derived from the test results and exhibits an even lower deviation than the simple curve fit. It also models the steps in the result values, since from theory the mean number of retransmissions is not an analytic function in T_{on} and T_{off}.

A.4.2 OBU10 results

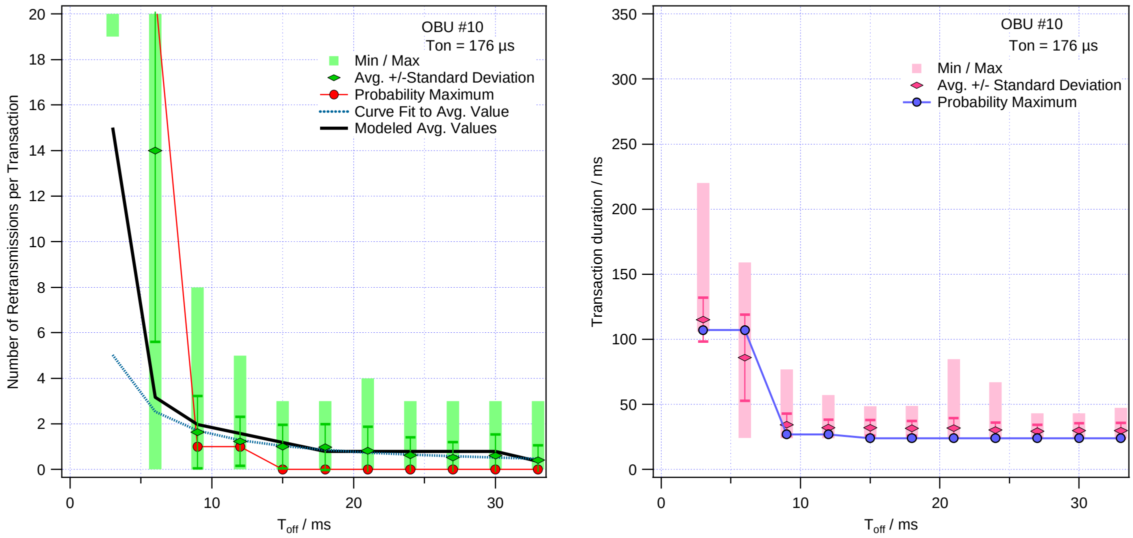


Figure A.26: TD_COEX_OBU_02 Test run 1

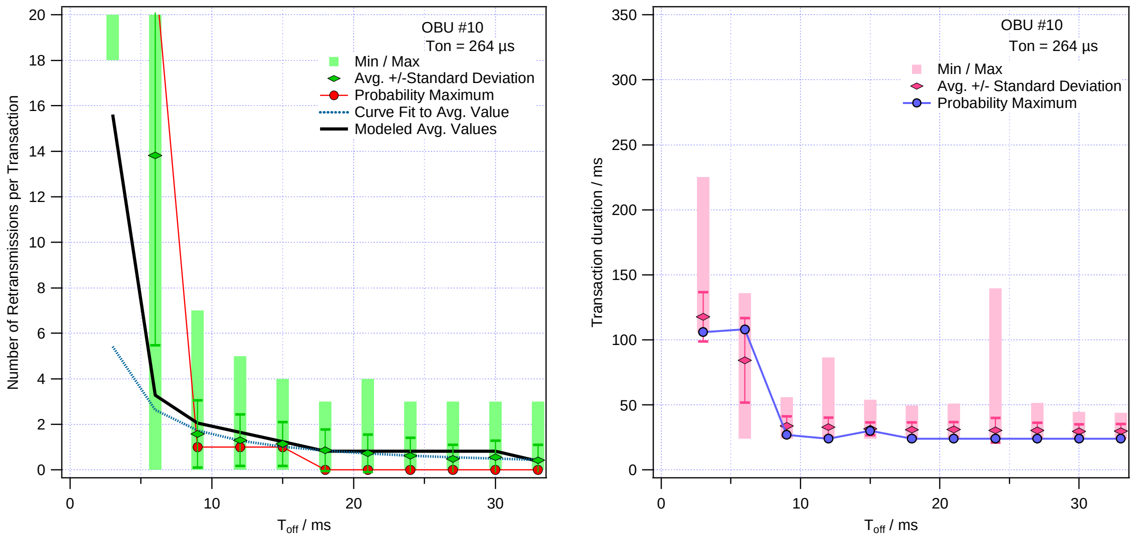


Figure A.27: TD_COEX_OBU_02 Test run 2

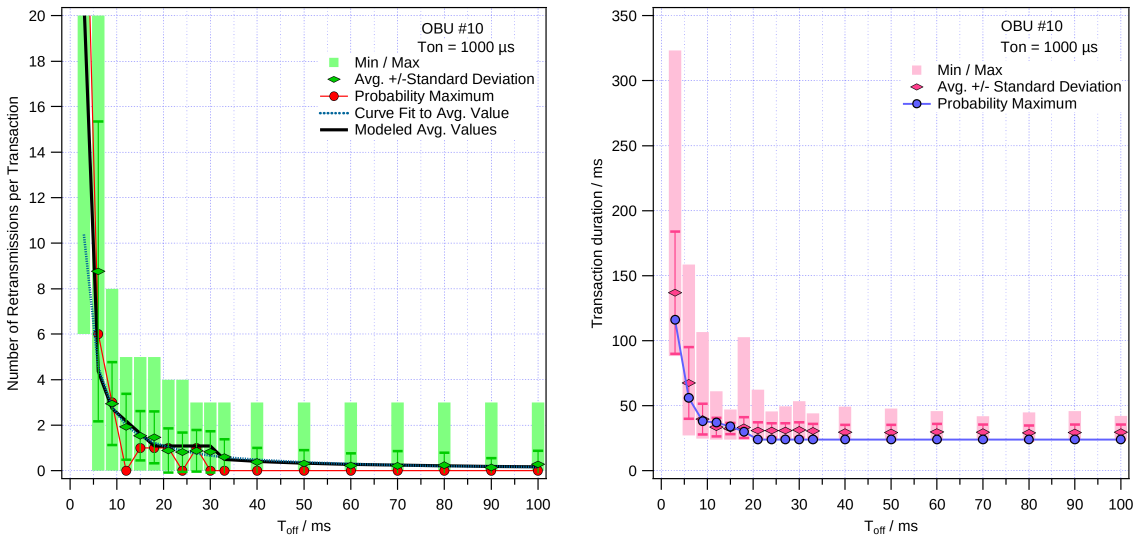


Figure A.28: TD_COEX_OBU_02 Test run 3

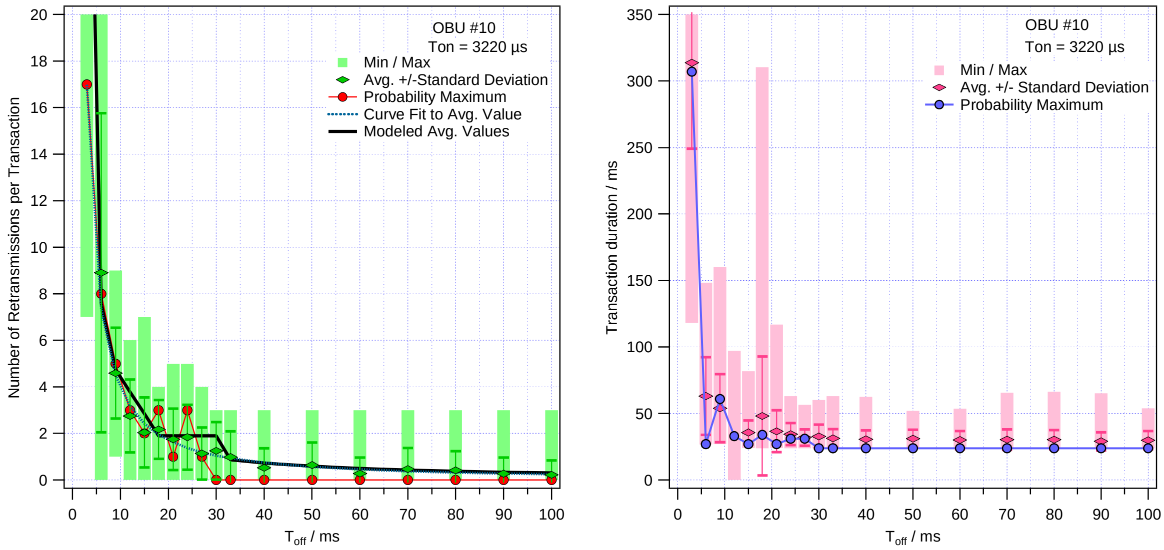


Figure A.29: TD_COEX_OBU_02 Test run 4

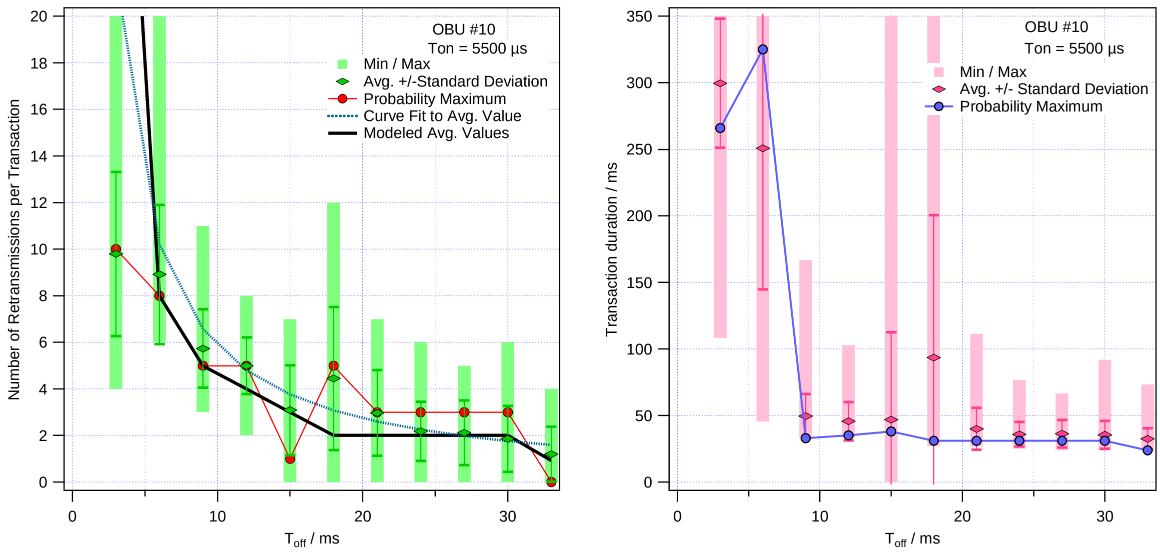


Figure A.30: TD_COEX_OBU_02 Test run 5

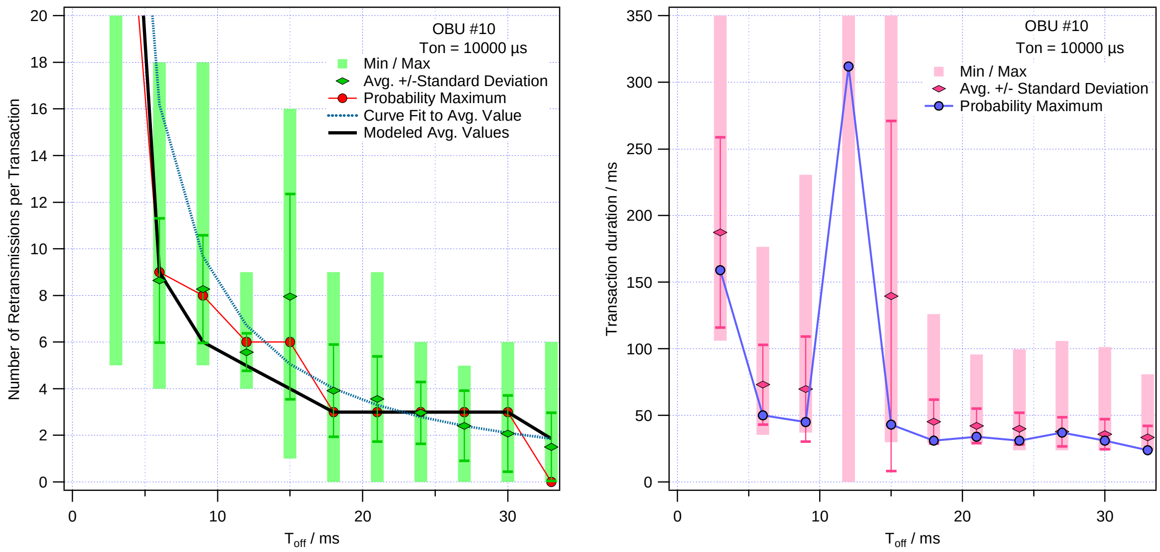


Figure A.31: TD_COEX_OBU_02 Test run 6

A.4.3 OBU12 results

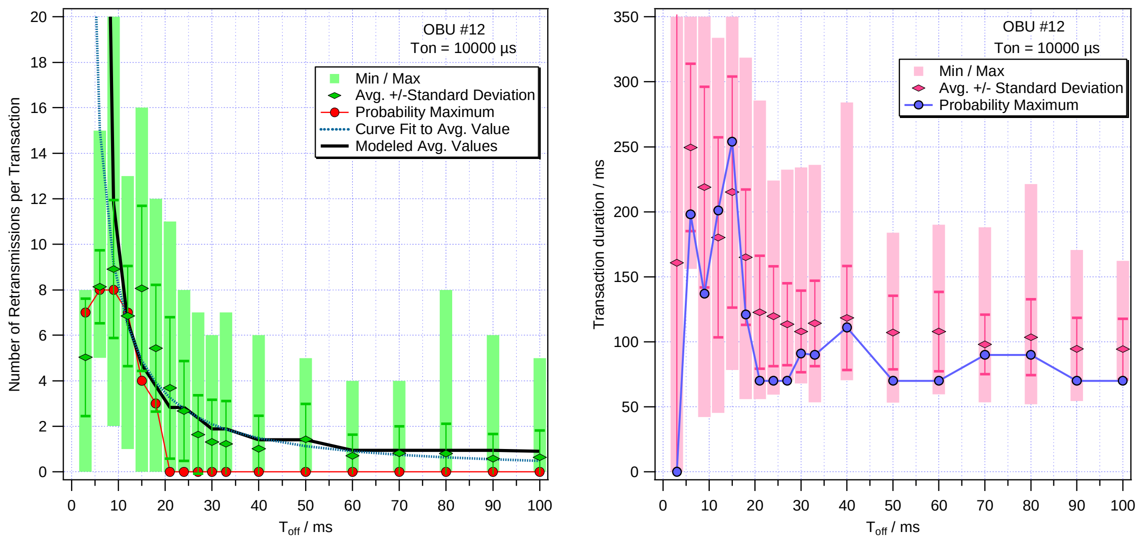


Figure A.32: TD_COEX_OBU_02 Test run 7

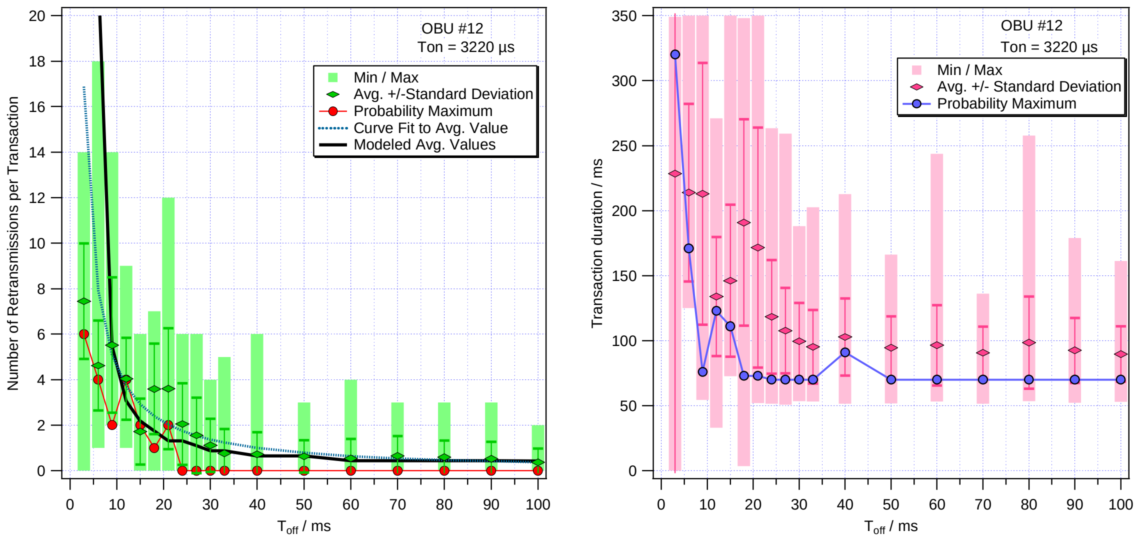


Figure A.33: TD_COEX_OBU_02 Test run 8

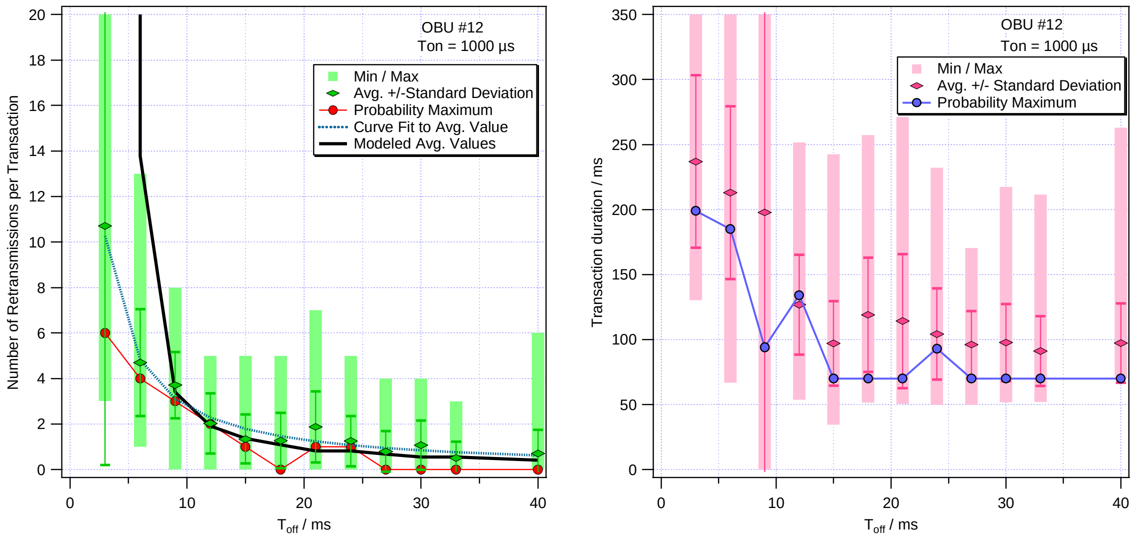


Figure A.34: TD_COEX_OBU_02 Test run 9

Detailed results of each test run are contained in the excel files:

TD_COEX_OBU_02 Test Run 1.xls

TD_COEX_OBU_02 Test Run 2.xls

TD_COEX_OBU_02 Test Run 3.xls

TD_COEX_OBU_02 Test Run 4.xls

TD_COEX_OBU_02 Test Run 5.xls

TD_COEX_OBU_02 Test Run 6.xls

TD_COEX_OBU_02 Test Run 7.xls

TD_COEX_OBU_02 Test Run 8.xls

TD_COEX_OBU_02 Test Run 9.xls

contained in archive tr_102960v010101p0.zip which accompanies the present document.

A.5 Measurement 3

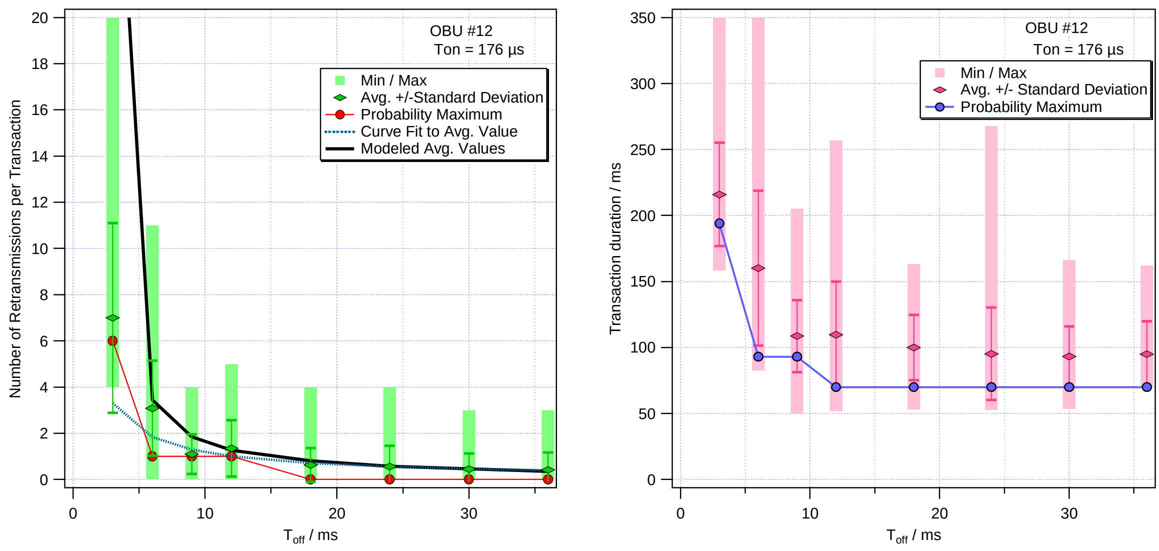


Figure A.35: TD_COEX_OBU_03 Test run 2

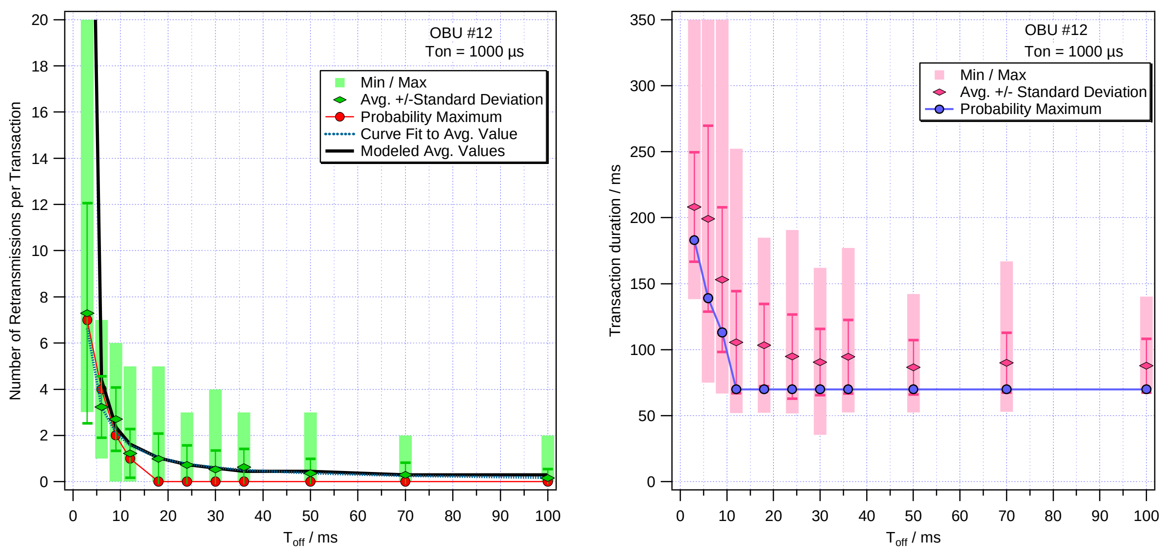


Figure A.36: TD_COEX_OBU_03 Test run 3

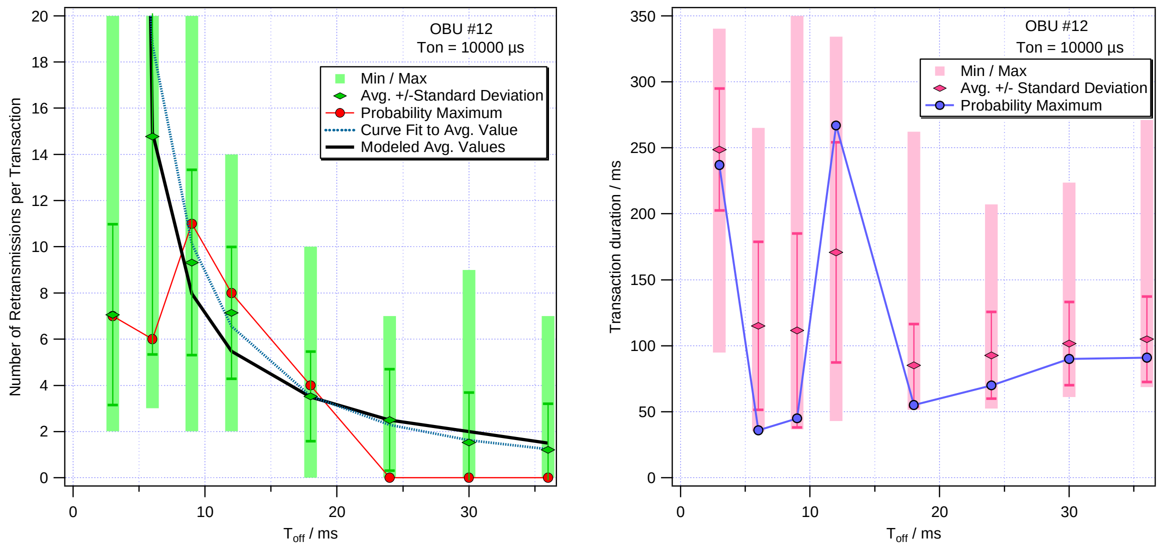


Figure A.37: TD_COEX_OBU_03 Test run 4

Detailed results of each test run are contained in the excel files:

TD_COEX_OBU_03 Test Run 1.xls

TD_COEX_OBU_03 Test Run 2.xls

TD_COEX_OBU_03 Test Run 3.xls

TD_COEX_OBU_03 Test Run 4.xls

contained in archive tr_102960v010101p0.zip which accompanies the present document.

Annex B: Models used for simulation and evaluation

B.1 Introduction

Annex B presents models used for simulations as described in clause 5 and the evaluation of the measurement results from clause 6.3.

B.2 CEN DSRC OBU antenna characteristics used in SEAMCAT and simulator 2

B.2.1 General antenna model properties

Since SEAMCAT is not able to apply statistic fading to the antenna pattern for every run, a fixed antenna model is used in the simulations. The TD_CAL_01 model uses the estimated worst case fading margin, while the models derived from TD_COEX_OBU_01 represent the fading by the real measurement fluctuations over azimuth. The fading statistic is indirectly reproduced, since the interferers are placed randomly for each simulation run.

The models derived from TD_COEX_OBU_01 directly define the interference power limit, which is the maximum incident ITS-G5 power level in front of the windscreen allowed to ensure coexistence.

SEAMCAT allows the input of a separate antenna peak gain as offset values of the antenna pattern to normalise the antenna diagram.

SEAMCAT does not support distinct vertical antenna patterns, therefore the same measured azimuth pattern is used independent of the elevation angle.

B.2.2 TD_CAL_01 antenna model

According to the reference measurement TD_CAL_01 as described in clause 6.2.3.1 an antenna model of the CEN DSRC OBU antenna has been developed.

Figure B.1 shows the estimated worst case fading margin of a typical CEN DSRC OBU evaluated from the measurement results of TD_CAL_01. The antenna model used for the SEAMCAT simulations was normalised to a maximum gain of 0 dBi (red curve in figure B.1).

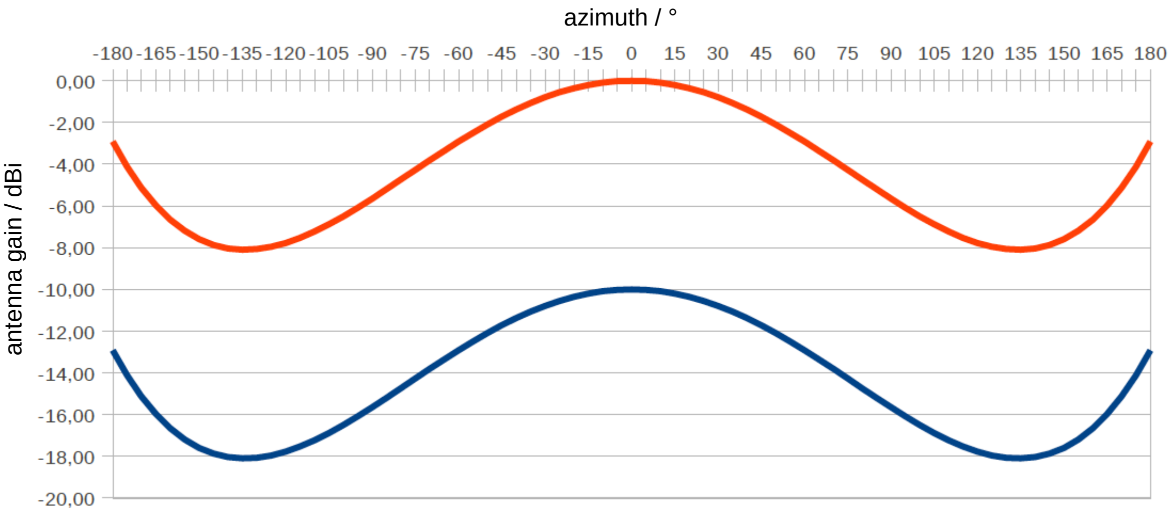


Figure B.1: Antenna model derived from TD_CAL_01, upper and lower fading margin

B.2.3 TD_COEX_OBU_01 run 1 interference limit pattern of OBU11

From the results of the 1st run of the measurement TD_COEX_OBU_01 as described in clause A.3.2.1, the interference power limit of the CEN DSRC OBU11 was evaluated and used for the SEAMCAT simulations (figure B.2).

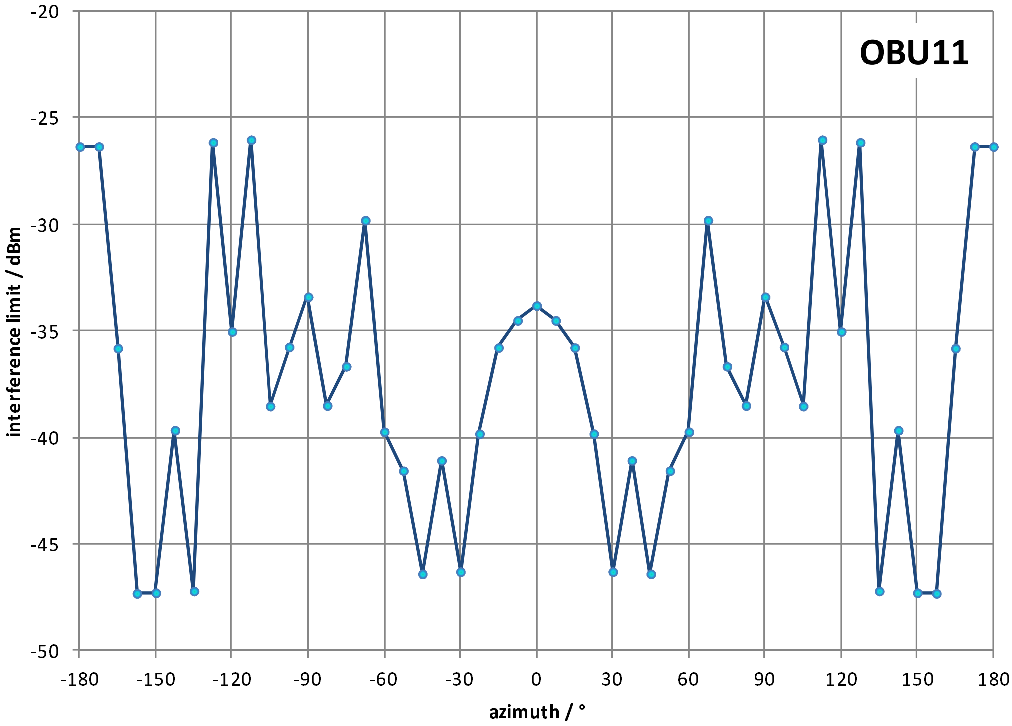


Figure B.2: Interference power limit for OBU11, from TD_COEX_OBU_01 run 1

B.2.4 TD_COEX_OBU_01 run 2 interference limit pattern of OBU2

From the results of the 2nd run of the measurement TD_COEX_OBU_01 as described in clause A.3.2.2, the interference power limit of the CEN DSRC OBU2 was evaluated and used for the SEAMCAT simulations (figure B.3).

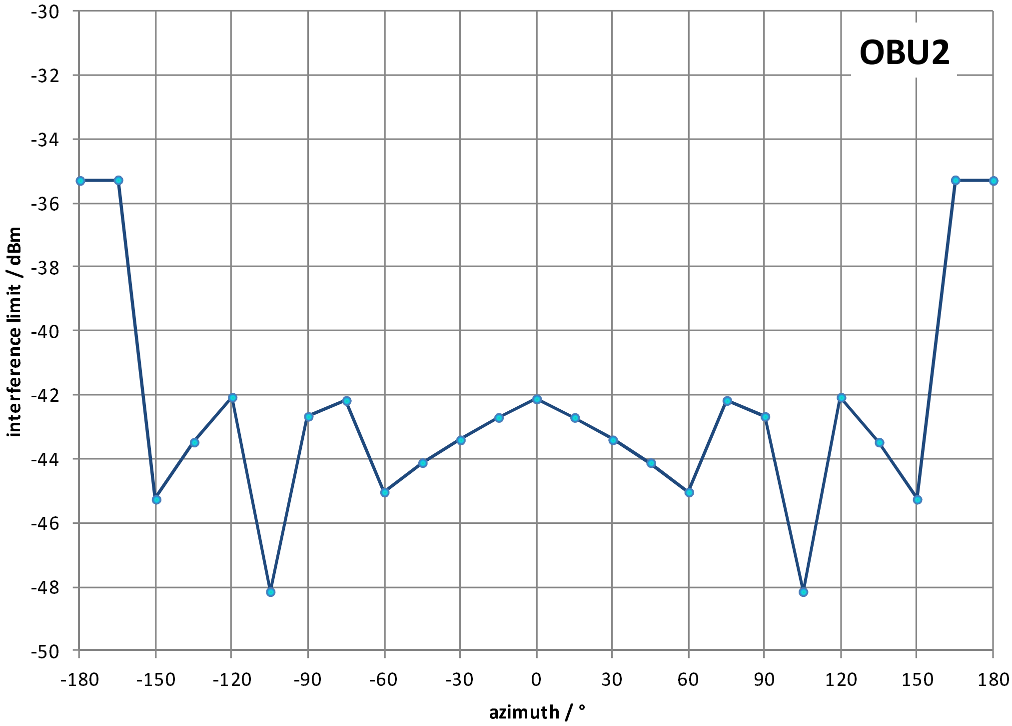


Figure B.3: Interference power limit for OBU2, from TD_COEX_OBU_01 run 2

B.2.5 TD_COEX_OBU_01 run 3 interference limit pattern of OBU10

From the results of the 3rd run of the measurement TD_COEX_OBU_01 as described in clause A.3.2.3, the interference power limit of the CEN DSRC OBU10 was evaluated and used for the SEAMCAT simulations (figure B.4).

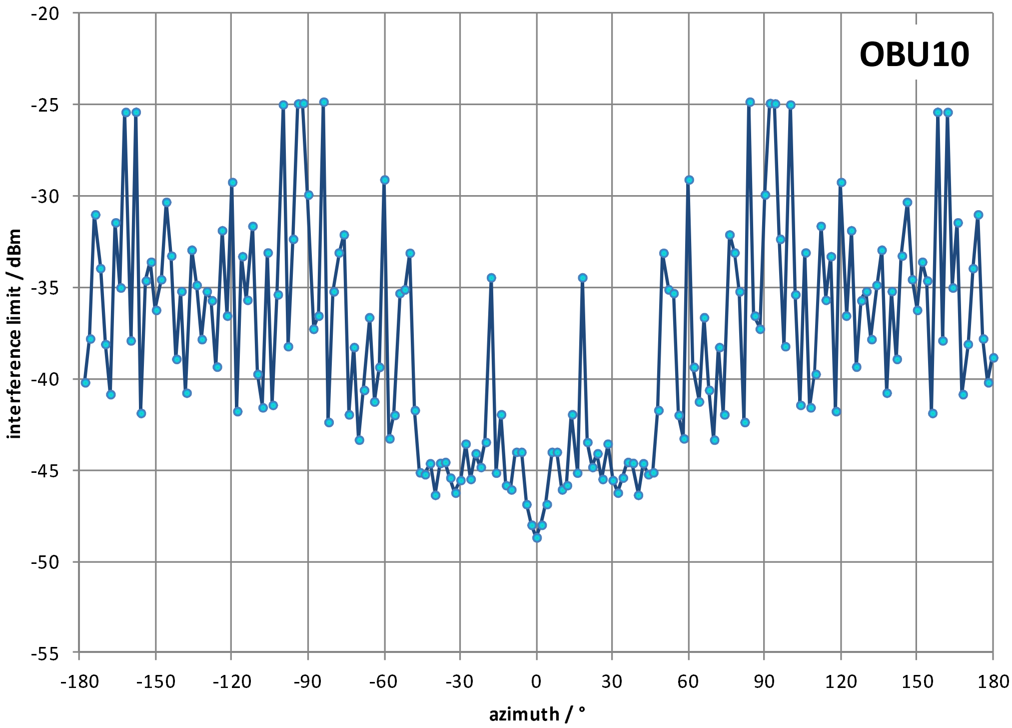


Figure B.4: Interference power limit for OBU10, from TD_COEX_OBU_01 run 3

B.2.6 TD_COEX_OBU_01 run 5 interference limit pattern of OBU6

From the results of the 5th run of the measurement TD_COEX_OBU_01 as described in clause A.3.2.5, the interference power limit of the CEN DSRC OBU6 was evaluated and used for the SEAMCAT simulations (figure B.5).

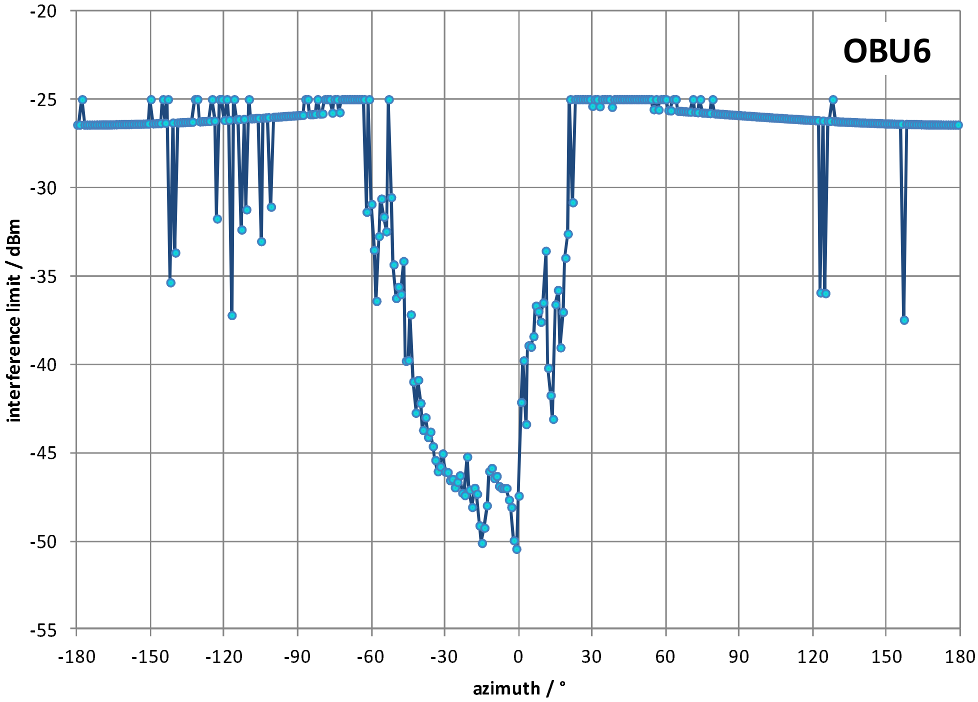


Figure B.5: Interference power limit for OBU6, from TD_COEX_OBU_01 run 5

B.2.7 TD_COEX_OBU_01 run 6 interference limit pattern of OBU9

From the results of the 6th run of the measurement TD_COEX_OBU_01 as described in clause A.3.2.6, the interference power limit of the CEN DSRC OBU9 was evaluated and used for the SEAMCAT simulations (figure B.6).

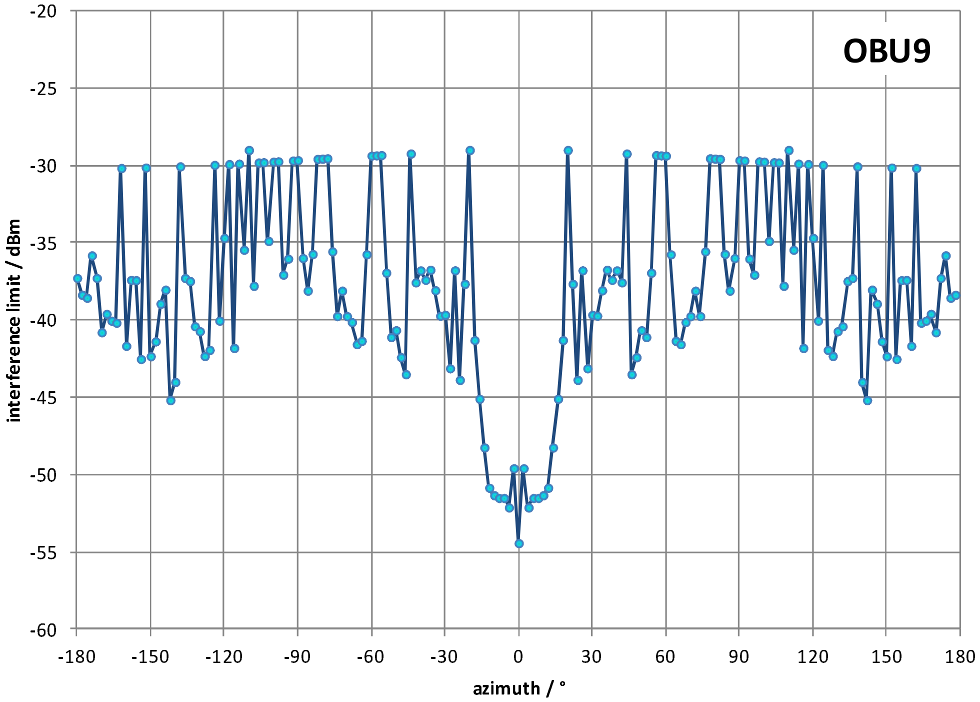


Figure B.6: Interference power limit for OBU9, from TD_COEX_OBU_01 run 6

Annex C: CEN DSRC protocol simulator details

C.1 Simulator configuration parameters

This clause includes a comprehensive list of all configuration parameters of the CEN DSRC protocol simulator (simulator 2):

- ITS-G5 configuration
  - Message configuration parameters
    - Message repetition rate
    - Message length
    - ITS power level
  - Channel Model parameters
    - Path loss coefficient
  - MAC / PHY parameters
    - AIFS
    - aSlotTime
    - CW_{min}
    - Message life time
    - Carrier sense level
    - RX Sensitivity
- Mobility simulator configuration
  - Lane setup parameters
    - Number of lanes
    - Lane width
    - Lane Start x-position
    - Lane End x-position
    - Lane centre y-position for each lane
  - Car setup parameters
    - Speed of cars per each lane
    - Time in between cars
    - Total number of cars

- CEN DSRC OBU configuration
    - OBU mounting parameters
        - OBU mounting height
        - OBU mounting angle
    - OBU RF parameters
        - OBU RX sensitivity
        - OBU conversion gain
        - OBU wake up sensitivity
        - Windscreen attenuation
        - OBU directivity parameter (antenna opening)
        - OBU BER slope (slope of BER model at OBU RX sensitivity level in dB/decade)
    - OBU interference parameters
        - OBU interference susceptibility pattern type
        - Maximum susceptibility value in OBU interference susceptibility pattern
- CEN DSRC RSU configuration
    - RSU mounting parameters
        - RSU mounting height
        - RSU mounting angle
    - RSU RF parameters
        - RSU RX sensitivity
        - RSU TX power level
        - RSU directivity parameter (antenna opening)
        - RSU BER slope (slope of BER model at RSU RX sensitivity level in dB/decade)
    - RSU interference parameters
        - Maximum susceptibility value in bore sight
(the susceptibility pattern is equivalent to the RSU antenna pattern)
- CEN DSRC transaction configuration
    - Common transaction setup parameters
        - BST repetition time
        - Twait
        - CEN DSRC Retry timeout
    - Private window request and allocation parameters
        - Len of private window request
        - Delay of private window allocation
        - Len of private window allocation

- Transaction timing parameters
    - Frame Type (BST/VST, GET/SET, or RELEASE)
    - Delay before request
    - Request length
    - Response length
    - Late response delay

C.2 CEN DSRC OBU simulator configuration details

From figure C.1 to figure C.8 this clause shows the CEN DSRC OBU simulator configuration dialog windows for all simulated OBUs.

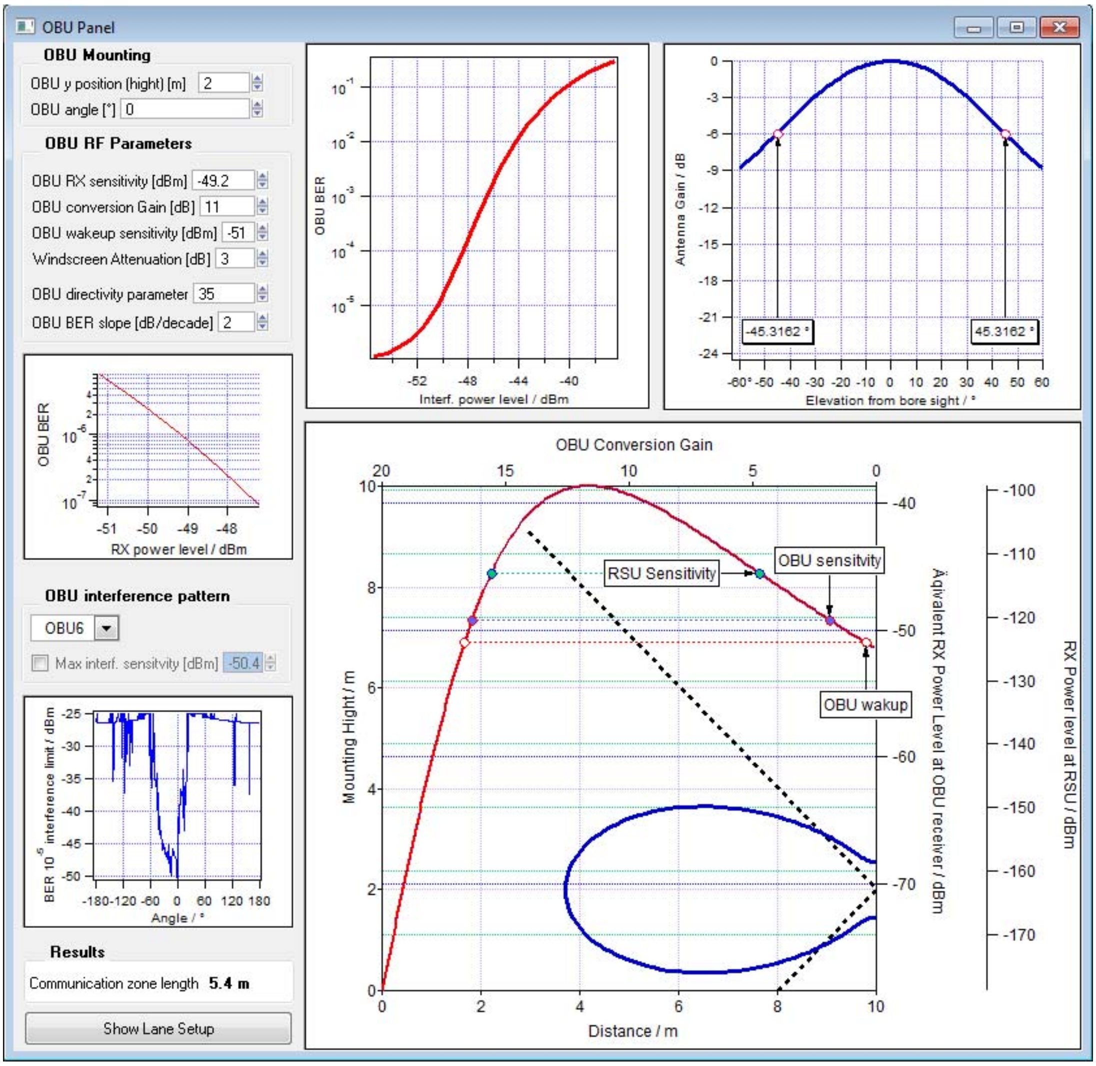
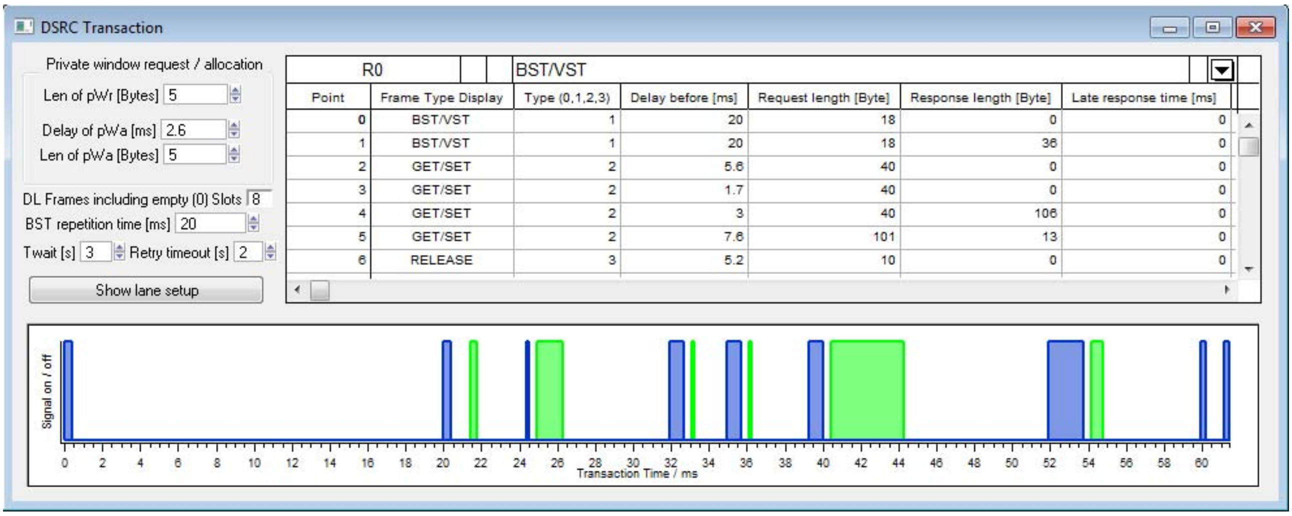


Figure C.1: RF, BER and interference susceptibility simulation parameters for OBU6



Point	Frame Type Display	Type (0,1,2,3)	Delay before [ms]	Request length [Byte]	Response length [Byte]	Late response time [ms]
0	BST/VST	1	20	18	0	0
1	BST/VST	1	20	18	36	0
2	GET/SET	2	5.6	40	0	0
3	GET/SET	2	1.7	40	0	0
4	GET/SET	2	3	40	106	0
5	GET/SET	2	7.6	101	13	0
6	RELEASE	3	5.2	10	0	0

Figure C.2: CEN DSRC transaction parameters for OBU6

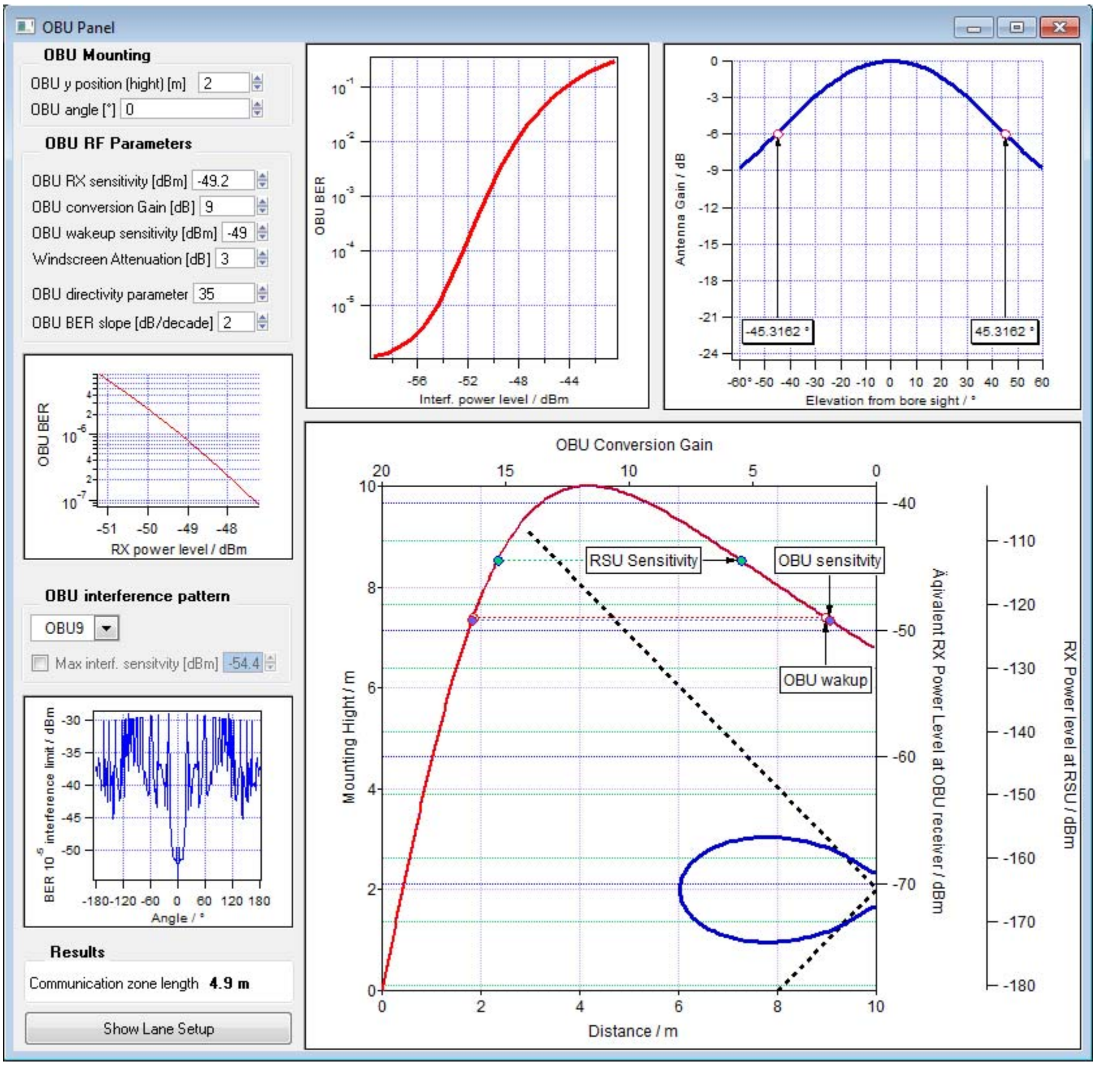


Figure C.3: RF, BER and interference susceptibility simulation parameters for OBU9

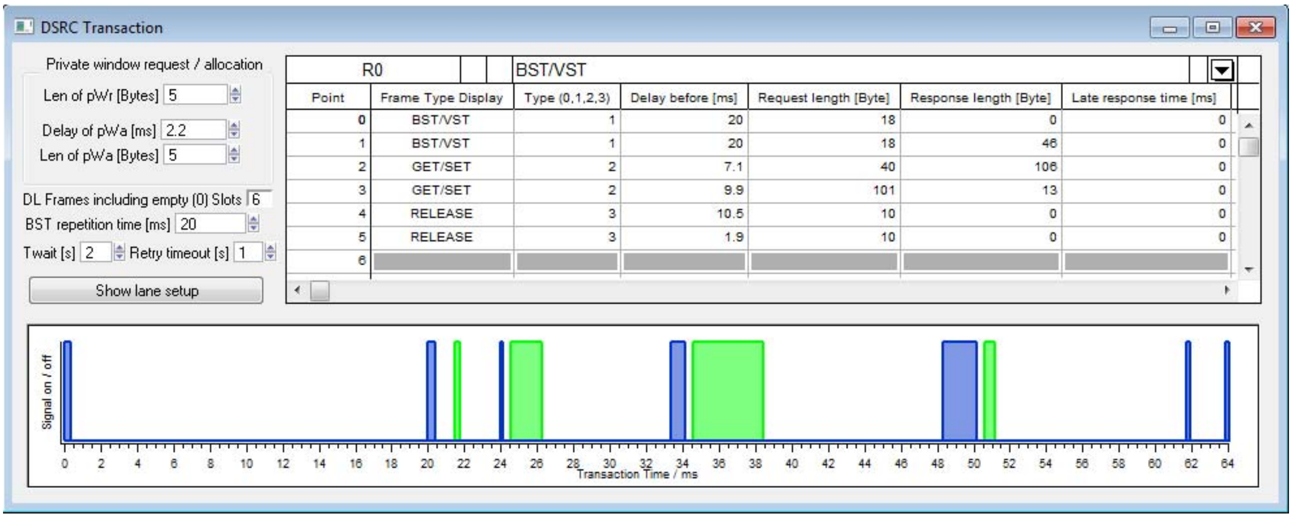


Figure C.4: CEN DSRC transaction parameters for OBU9

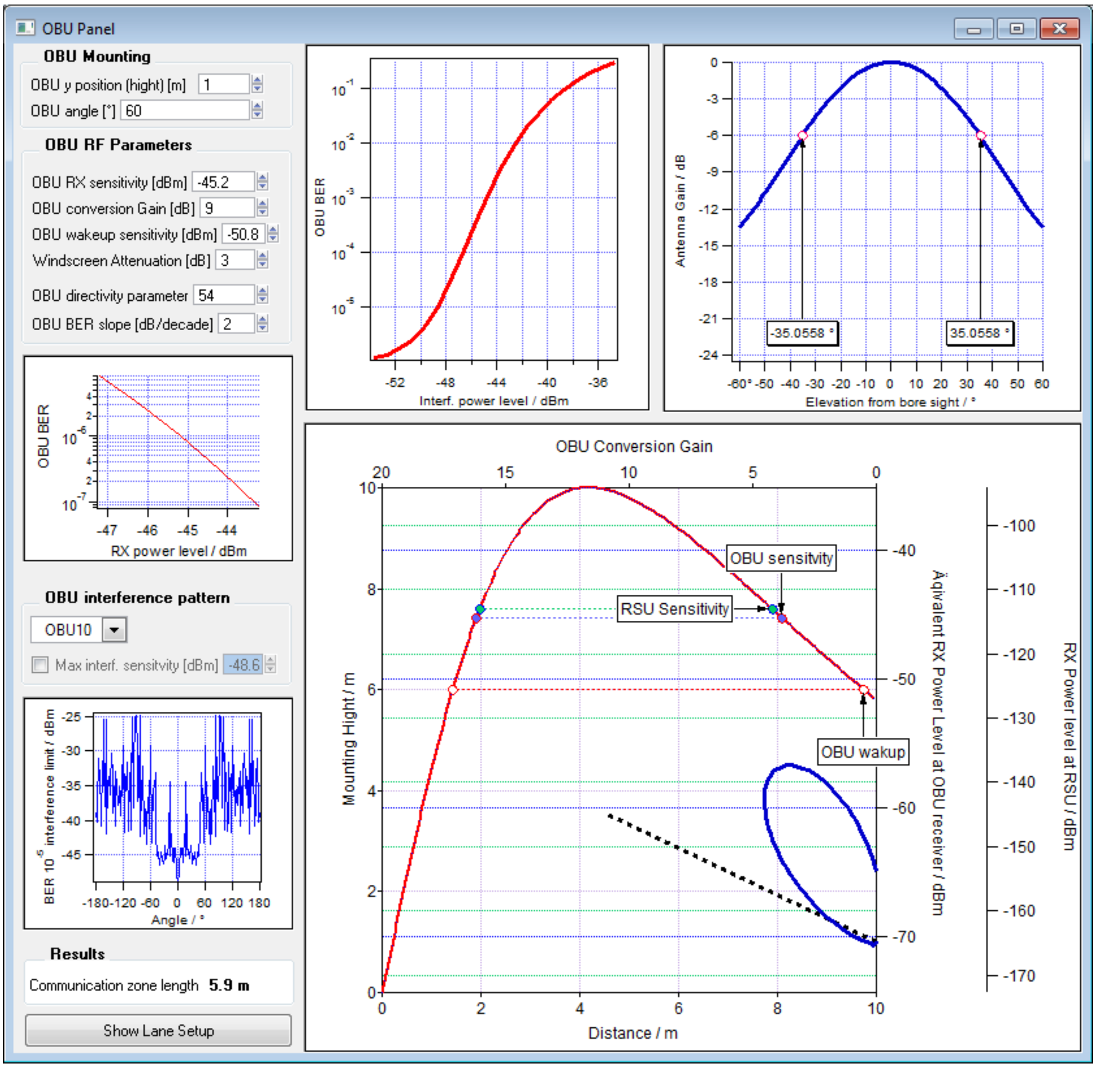


Figure C.5: RF, BER and interference susceptibility simulation parameters for OBU10

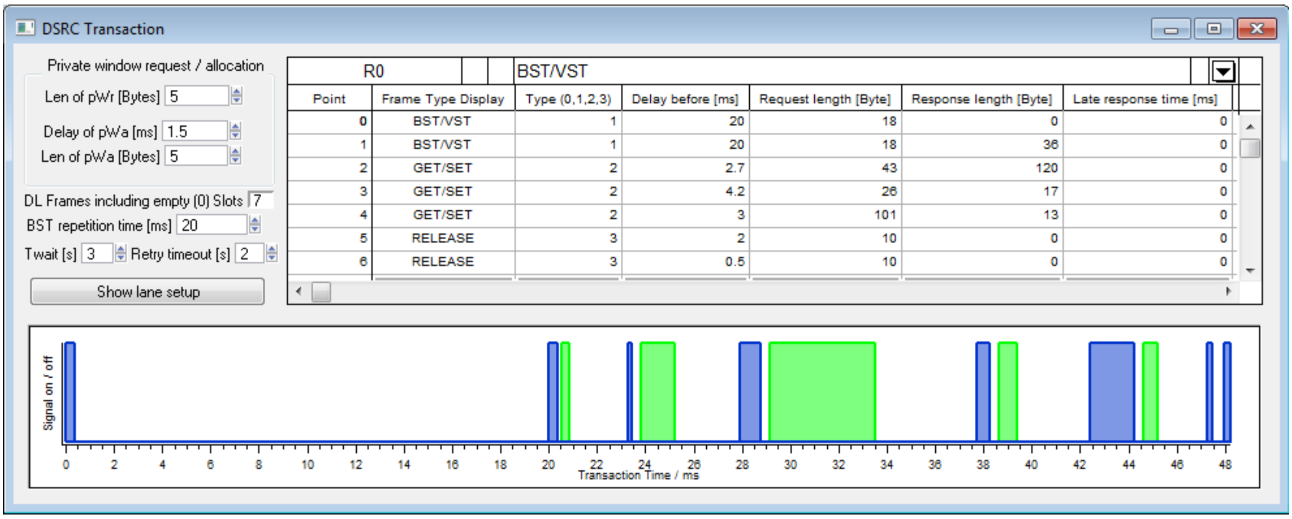


Figure C.6: CEN DSRC transaction parameters for OBU10

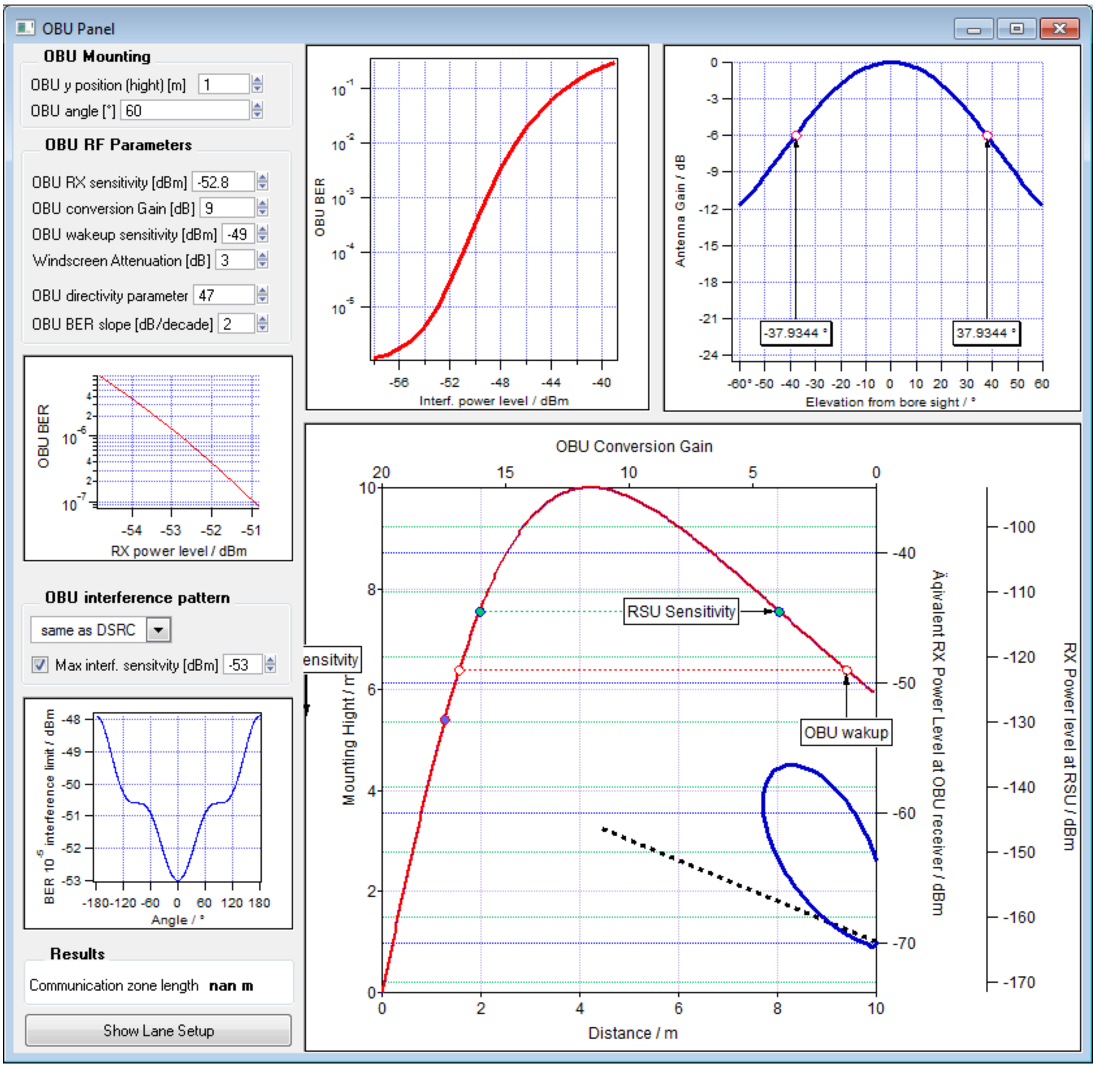


Figure C.7: RF, BER and interference susceptibility simulation parameters for OBU12

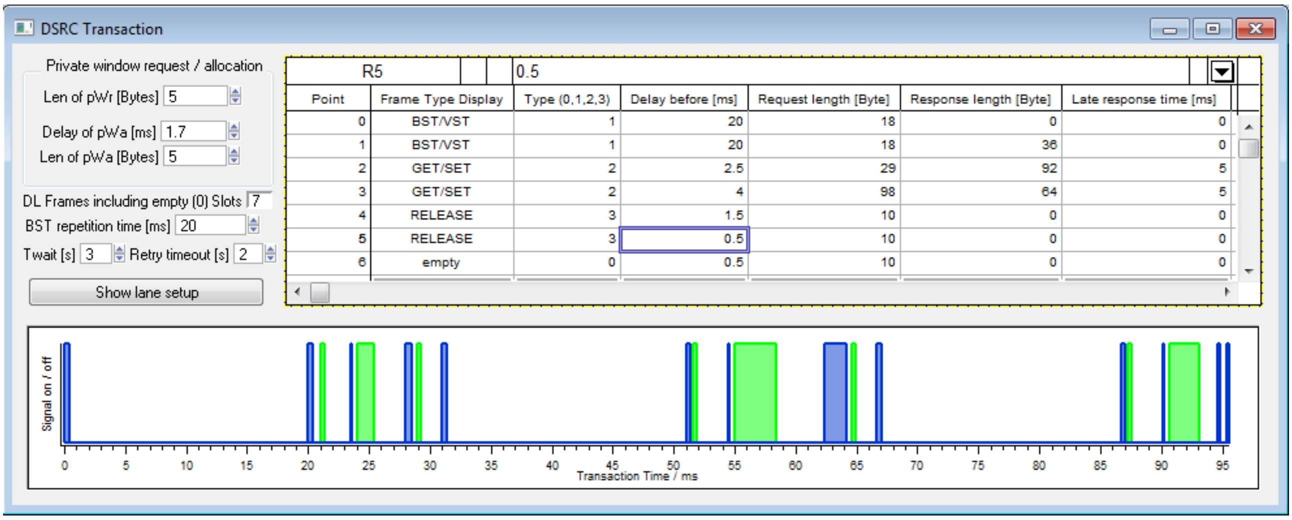


Figure C.8: CEN DSRC transaction parameters for OBU12

C.3 CEN DSRC OBU simulator simulation results

C.3.1 OBU9

C.3.1.1 Interference to one OBU9

The following simulation results of the CEN DSRC protocol simulator (simulator 2) are described in clause 5.4.4.2.

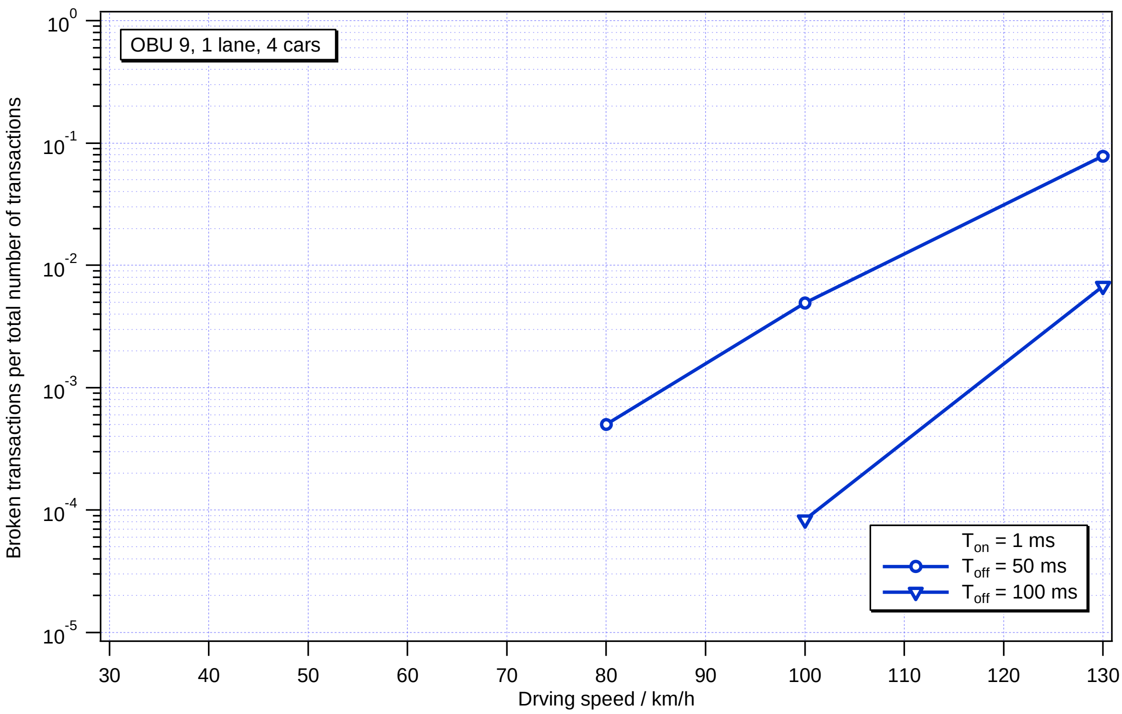


Figure C.9: Simulated ratio of potentially broken transactions at different speeds, caused by 4 interferers (cars), with an activity time T_{on} = 1 ms, to a CEN DSRC transactions with OBU9

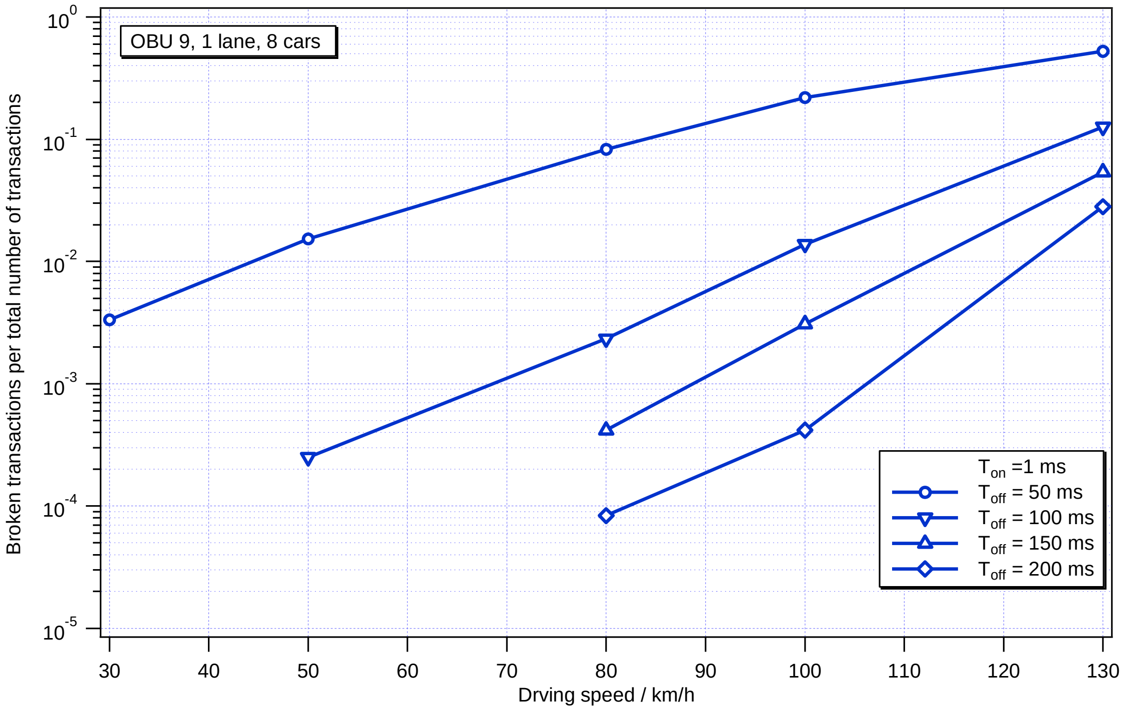


Figure C.10: Simulated ratio of potentially broken transactions at different speeds, caused by 8 interferers (cars), with an activity time T_{on} = 1 ms, to a CEN DSRC transactions with OBU9

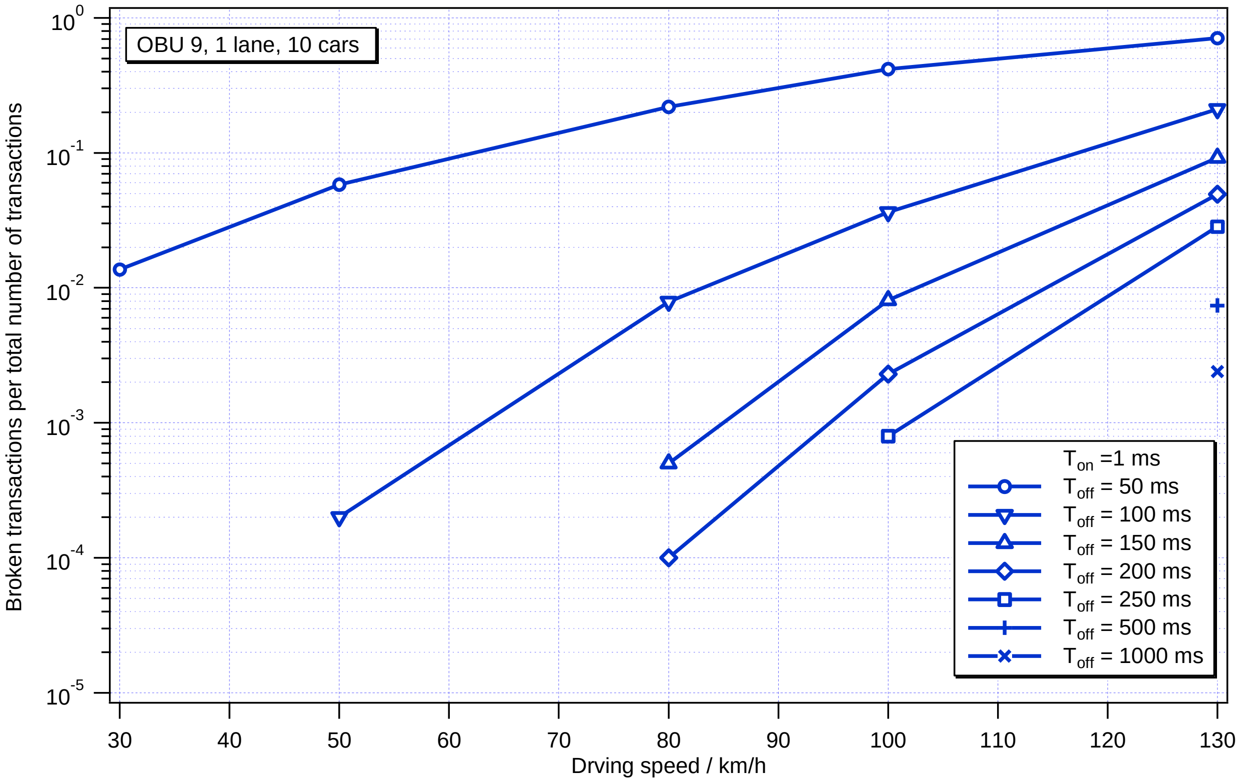


Figure C.11: Simulated ratio of potentially broken transactions at different speeds, caused by 10 interferers (cars), with an activity time T_{on} = 1 ms, to a CEN DSRC transactions with OBU9

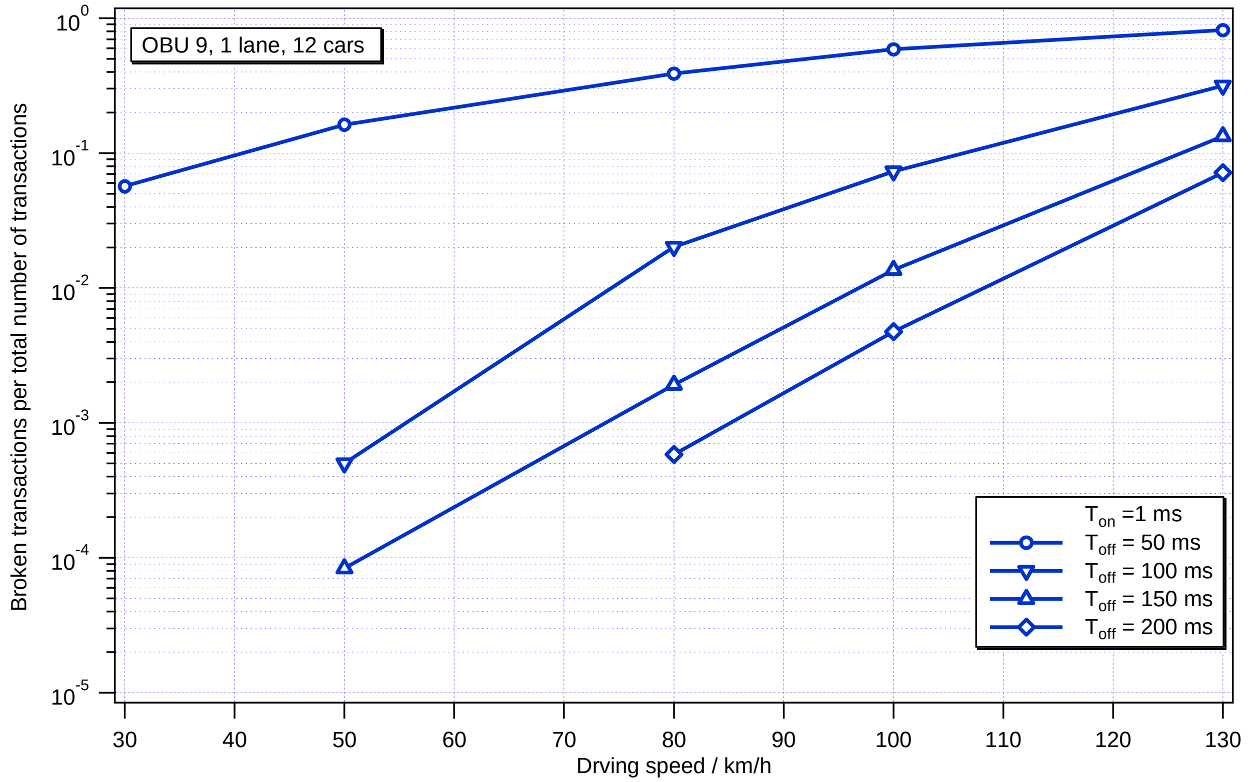


Figure C.12: Simulated ratio of potentially broken transactions at different speeds, caused by 12 interferers (cars), with an activity time T_{on} = 1 ms, to a CEN DSRC transactions with OBU9

C.3.1.2 Interference to two simultaneous CEN DSRC transactions with OBU9

The following simulation results of the CEN DSRC protocol simulator (simulator 2) are described in clause 5.4.4.3.

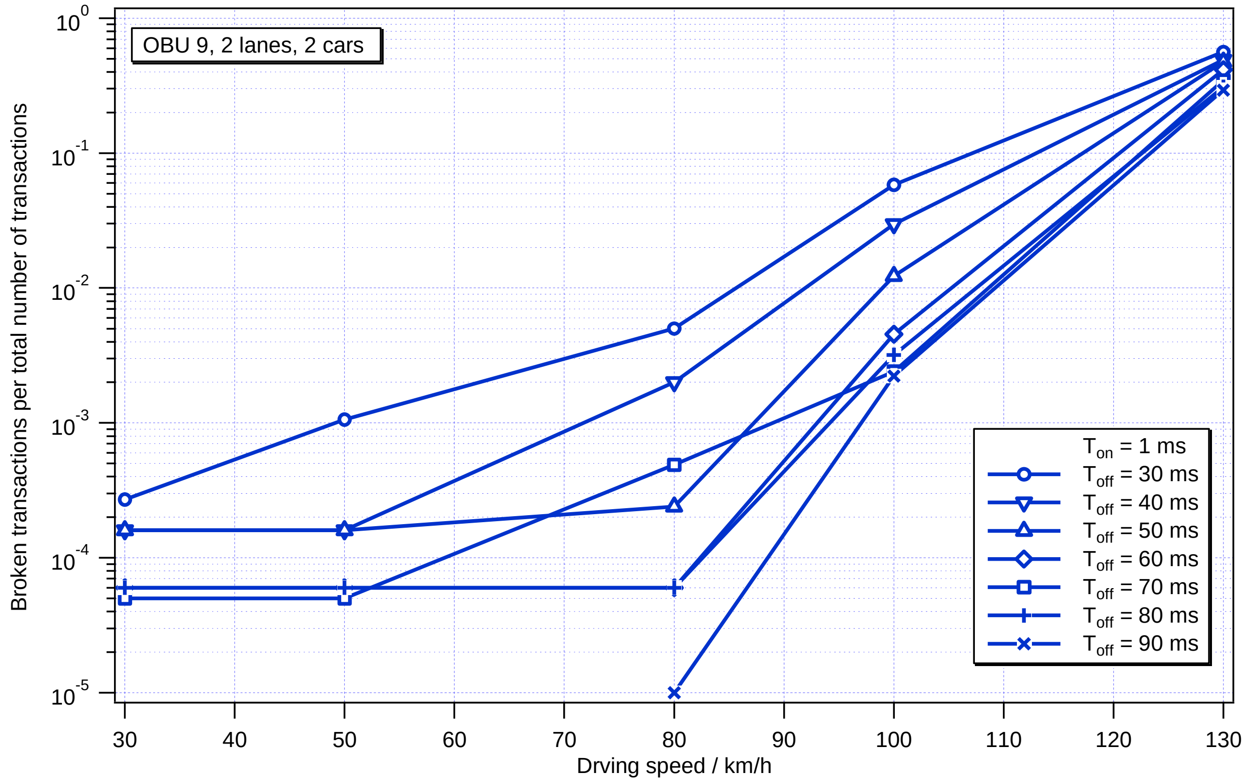


Figure C.13: Simulated ratio of potentially broken transactions at different speeds, caused by 2 interferers (cars), with an activity time T_{on} = 1 ms, to two concurrent CEN DSRC transactions with OBU9

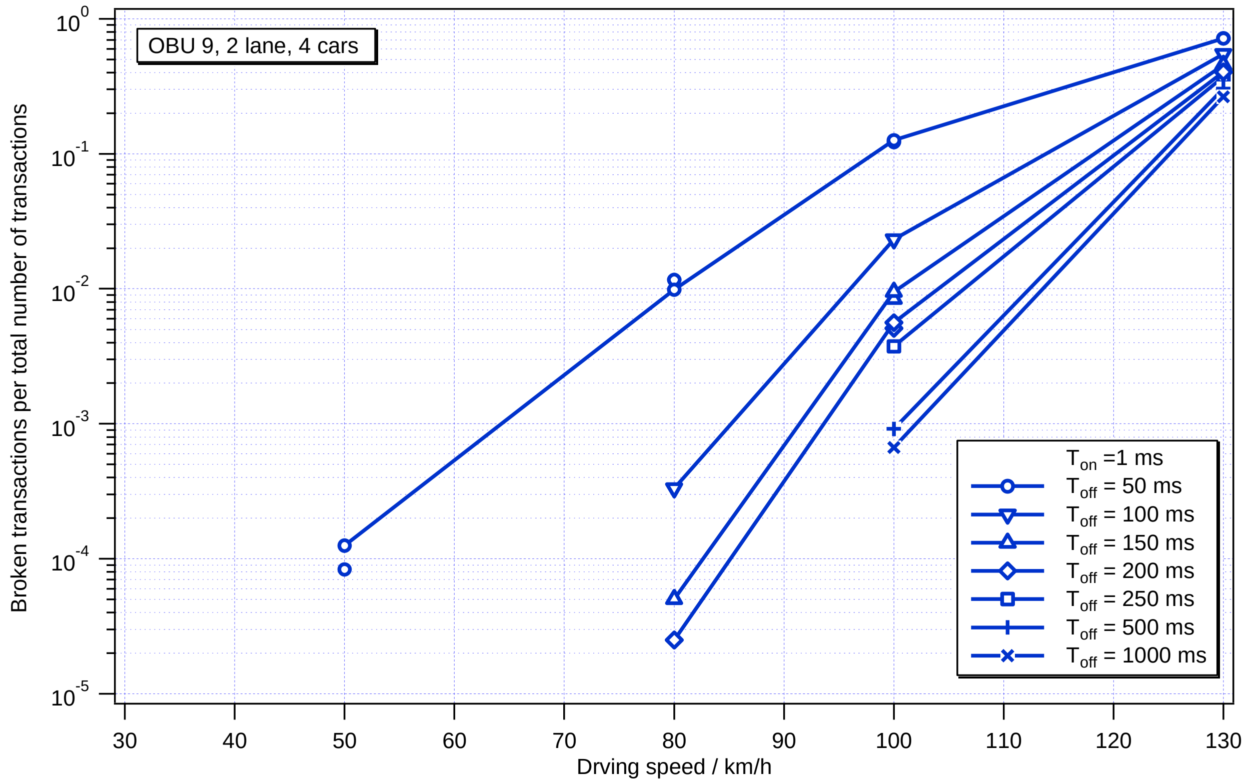


Figure C.14: Simulated ratio of potentially broken transactions at different speeds, caused by 4 interferers (cars), with an activity time T_{on} = 1 ms, to two concurrent CEN DSRC transactions with OBU9

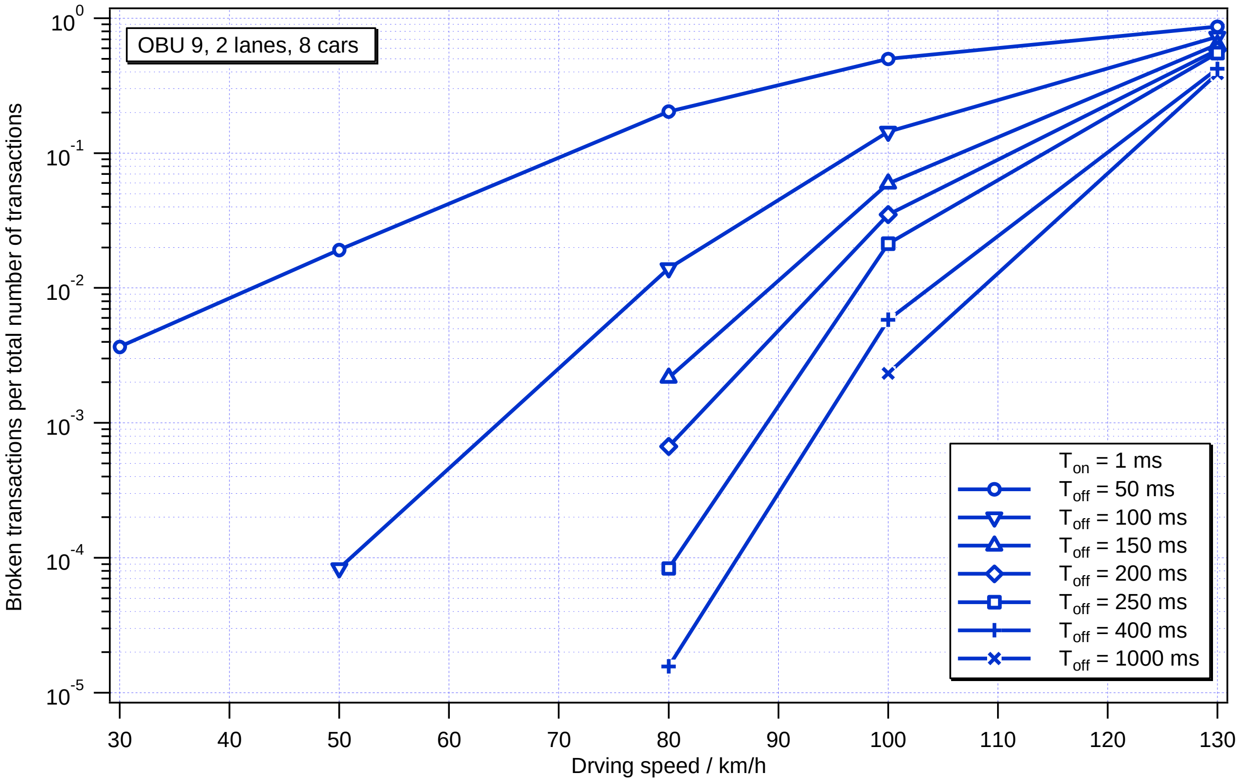


Figure C.15: Simulated ratio of potentially broken transactions at different speeds, caused by 8 interferers (cars), with an activity time T_{on} = 1 ms, to two concurrent CEN DSRC transactions with OBU9

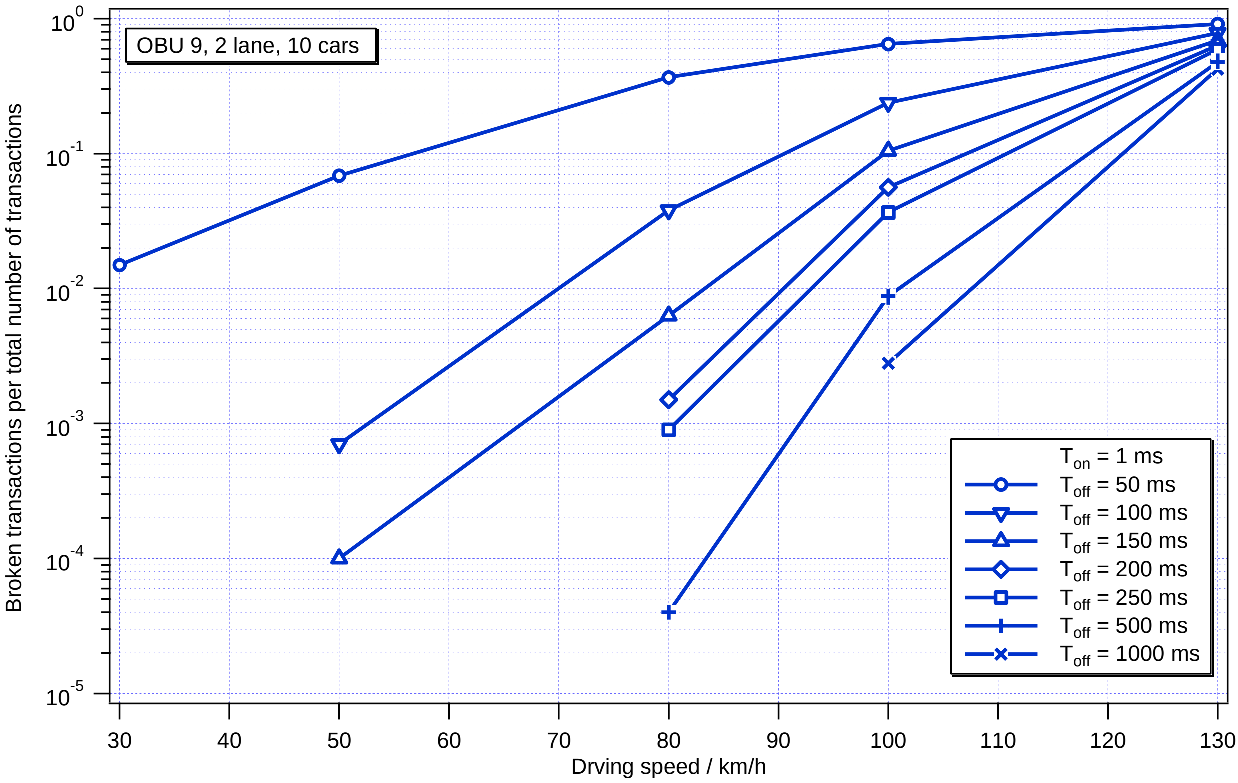


Figure C.16: Simulated ratio of potentially broken transactions at different speeds, caused by 10 interferers (cars), with an activity time T_{on} = 1 ms, to two concurrent CEN DSRC transactions with OBU9

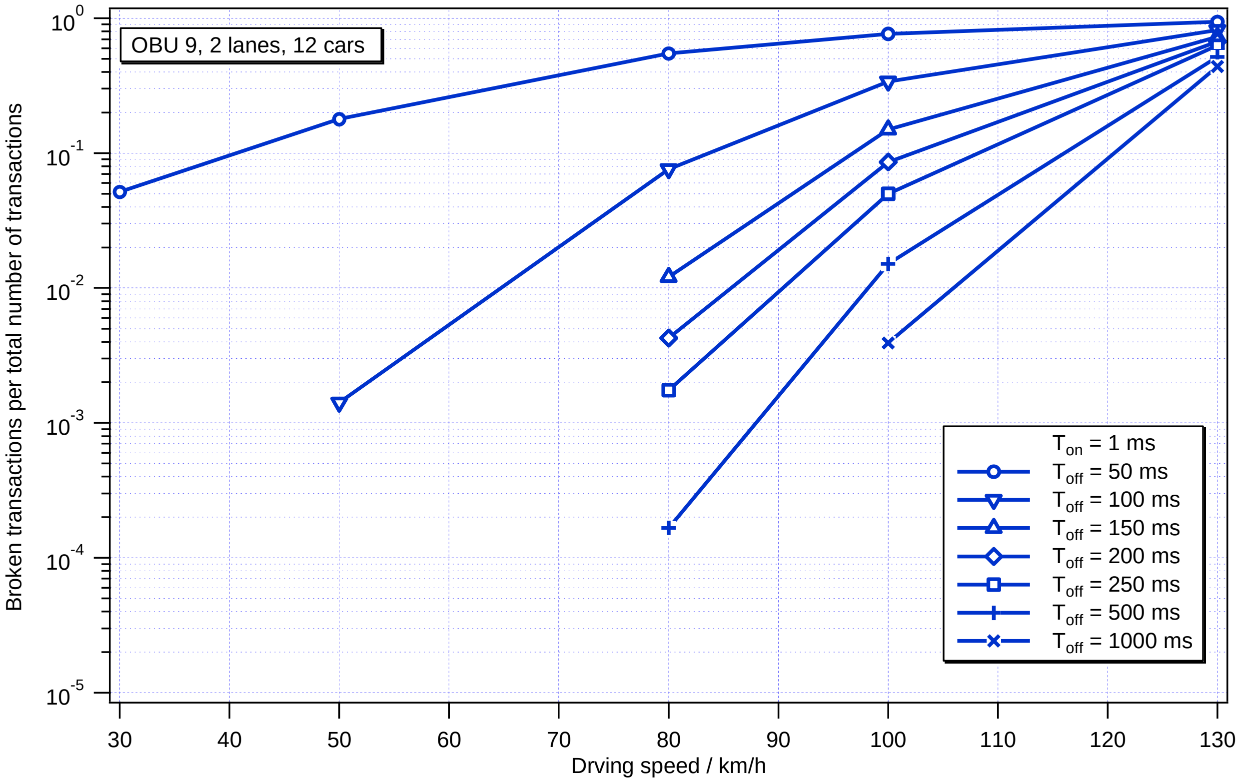


Figure C.17: Simulated ratio of potentially broken transactions at different speeds, caused by 12 interferers (cars), with an activity time T_{on} = 1 ms, to two concurrent CEN DSRC transactions with OBU9

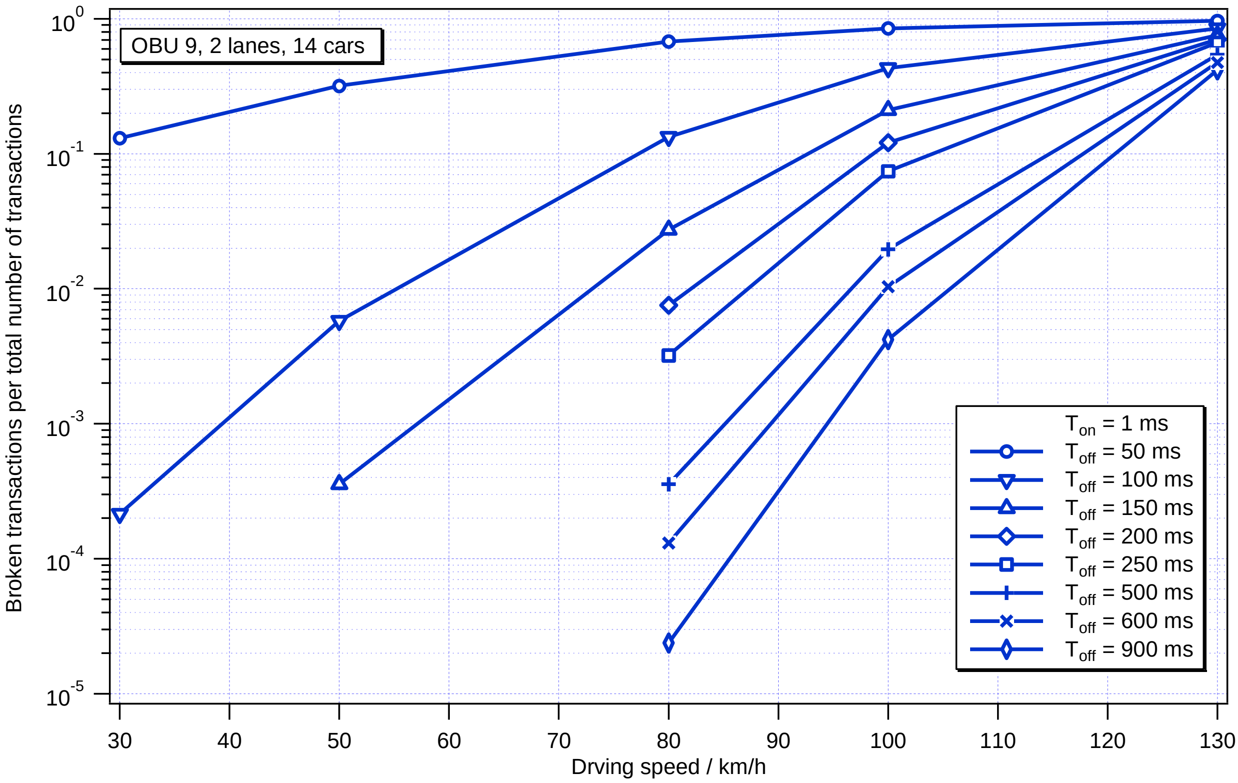


Figure C.18: Simulated ratio of potentially broken transactions at different speeds, caused by 14 interferers (cars), with an activity time T_{on} = 1 ms, to two concurrent CEN DSRC transactions with OBU9

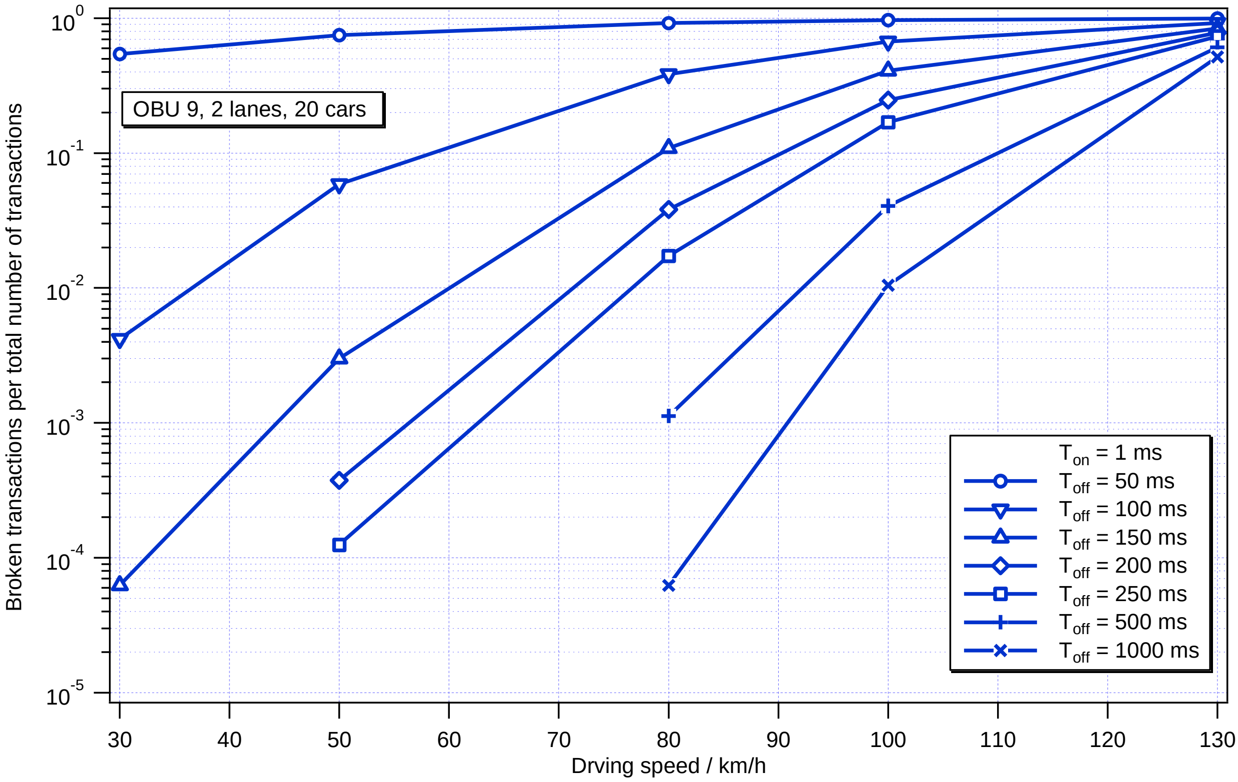


Figure C.19: Simulated ratio of potentially broken transactions at different speeds, caused by 20 interferers (cars), with an activity time T_{on} = 1 ms, to two concurrent CEN DSRC transactions with OBU9

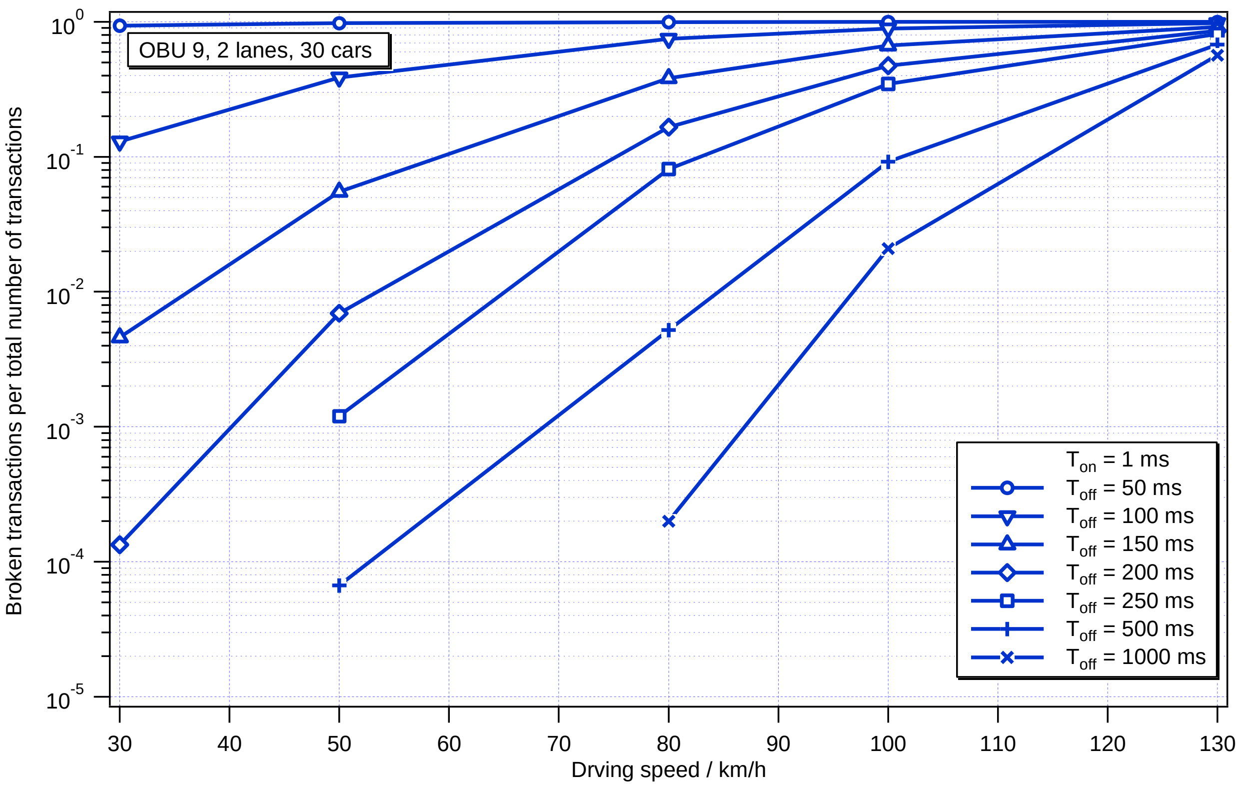


Figure C.20: Simulated ratio of potentially broken transactions at different speeds, caused by 30 interferers (cars), with an activity time T_{on} = 1 ms, to two concurrent CEN DSRC transactions with OBU9

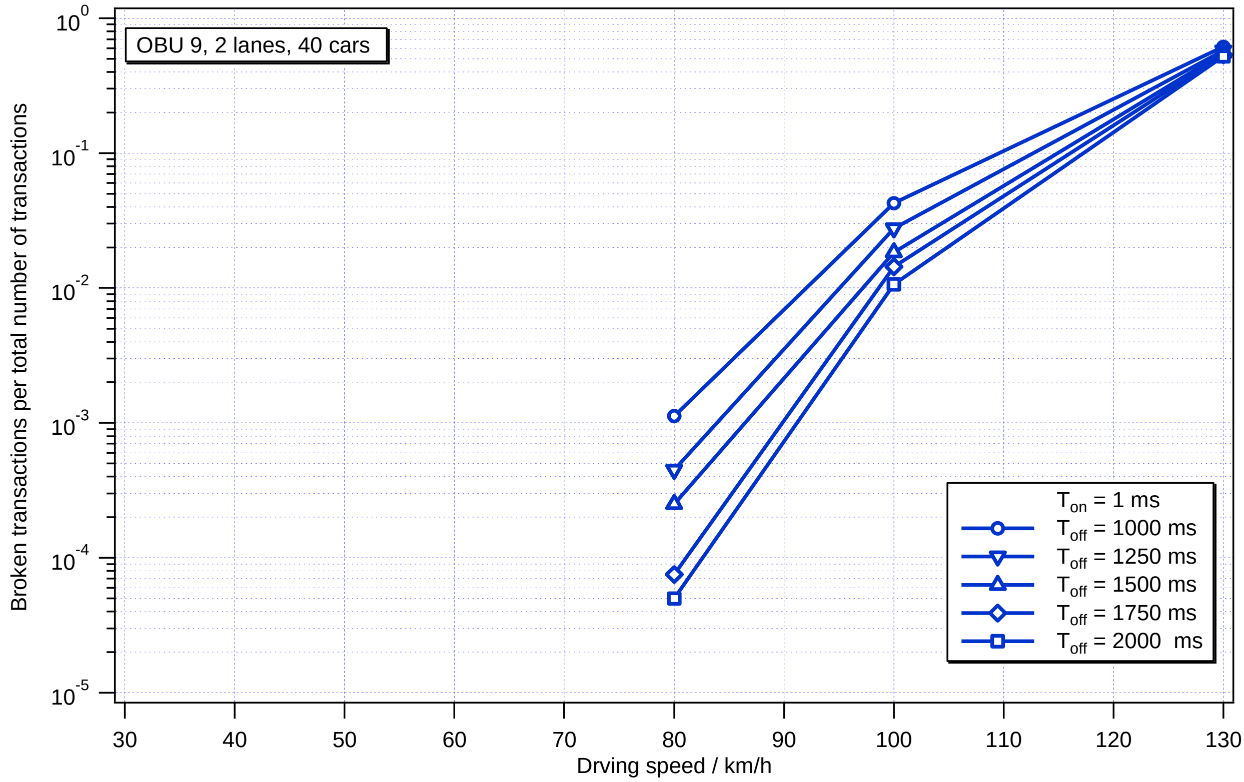


Figure C.21: Simulated ratio of potentially broken transactions at different speeds, caused by 40 interferers (cars), with an activity time T_{on} = 1 ms, to two concurrent CEN DSRC transactions with OBU9

C.3.1.3 Interference to 3 simultaneous CEN DSRC transactions with OBU9

The following simulation results of the CEN DSRC protocol simulator (simulator 2) are described in clause 5.4.4.4.

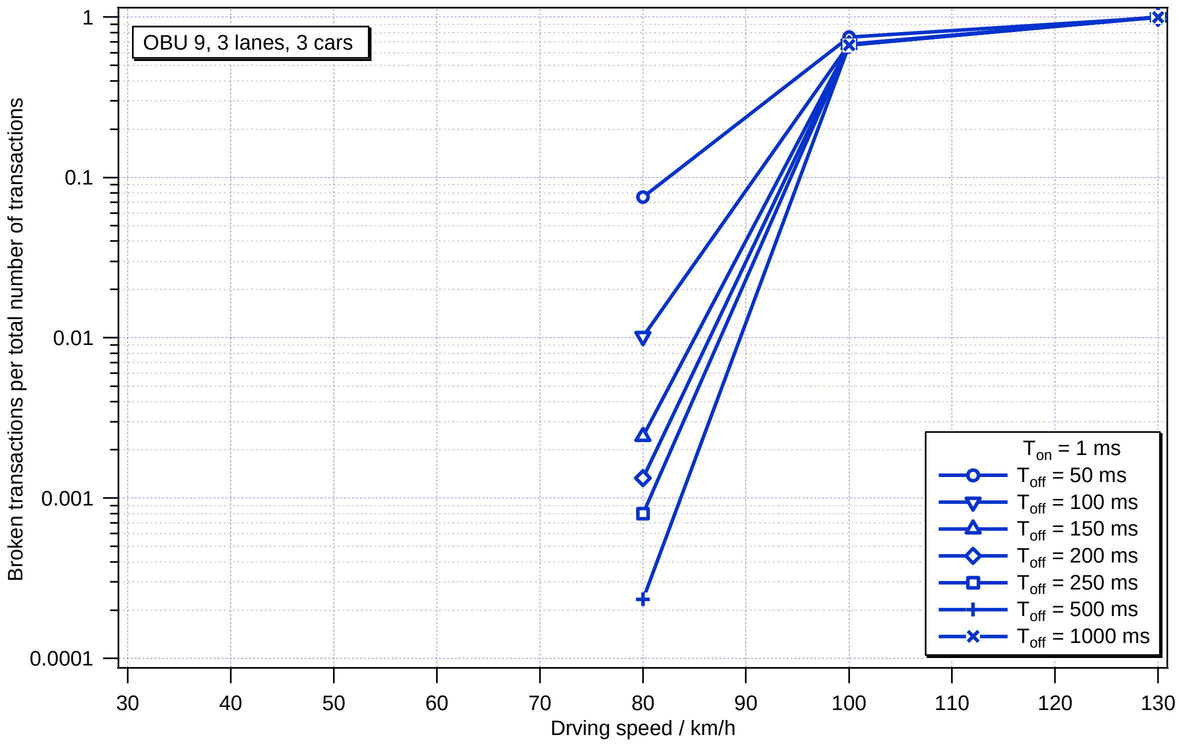


Figure C.22: Simulated ratio of potentially broken transactions at different speeds, caused by 3 interferers (cars), with an activity time T_{on} = 1 ms, to 3 concurrent CEN DSRC transactions with OBU9

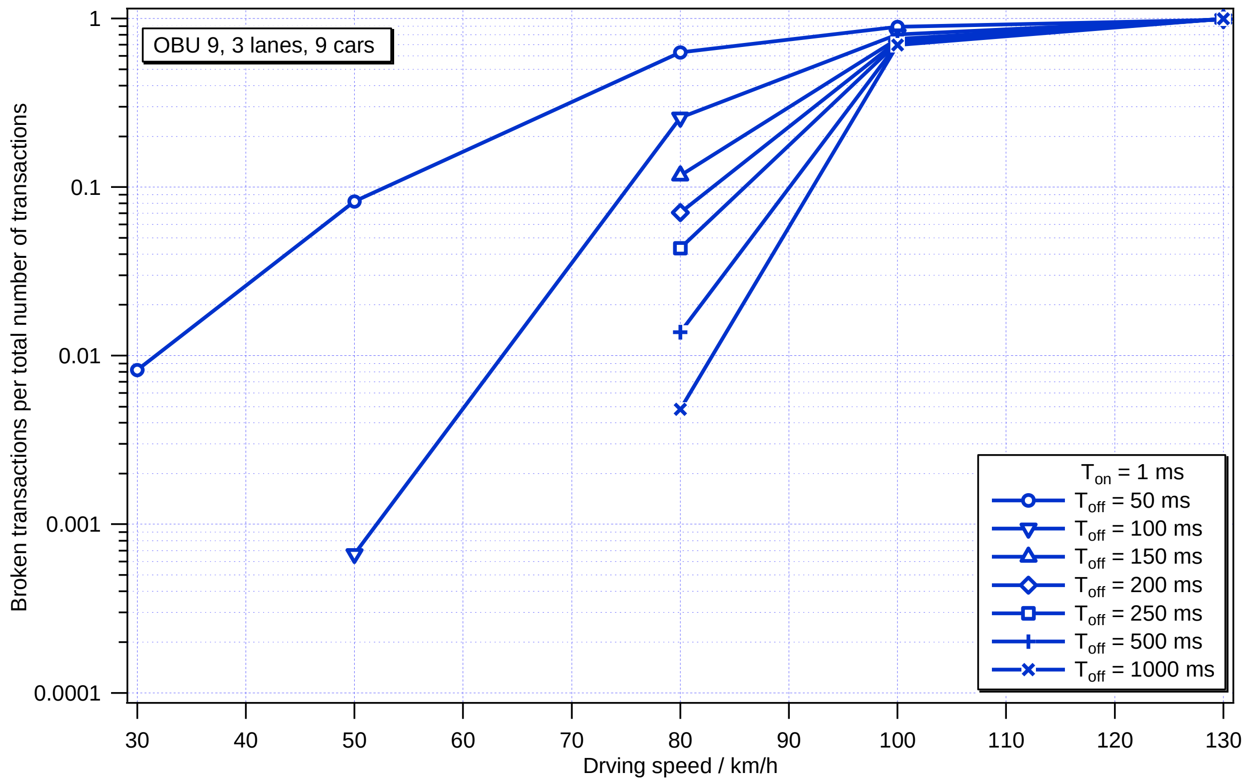


Figure C.23: Simulated ratio of potentially broken transactions at different speeds, caused by 9 interferers (cars), with an activity time T_{on} = 1 ms, to 3 concurrent CEN DSRC transactions with OBU9

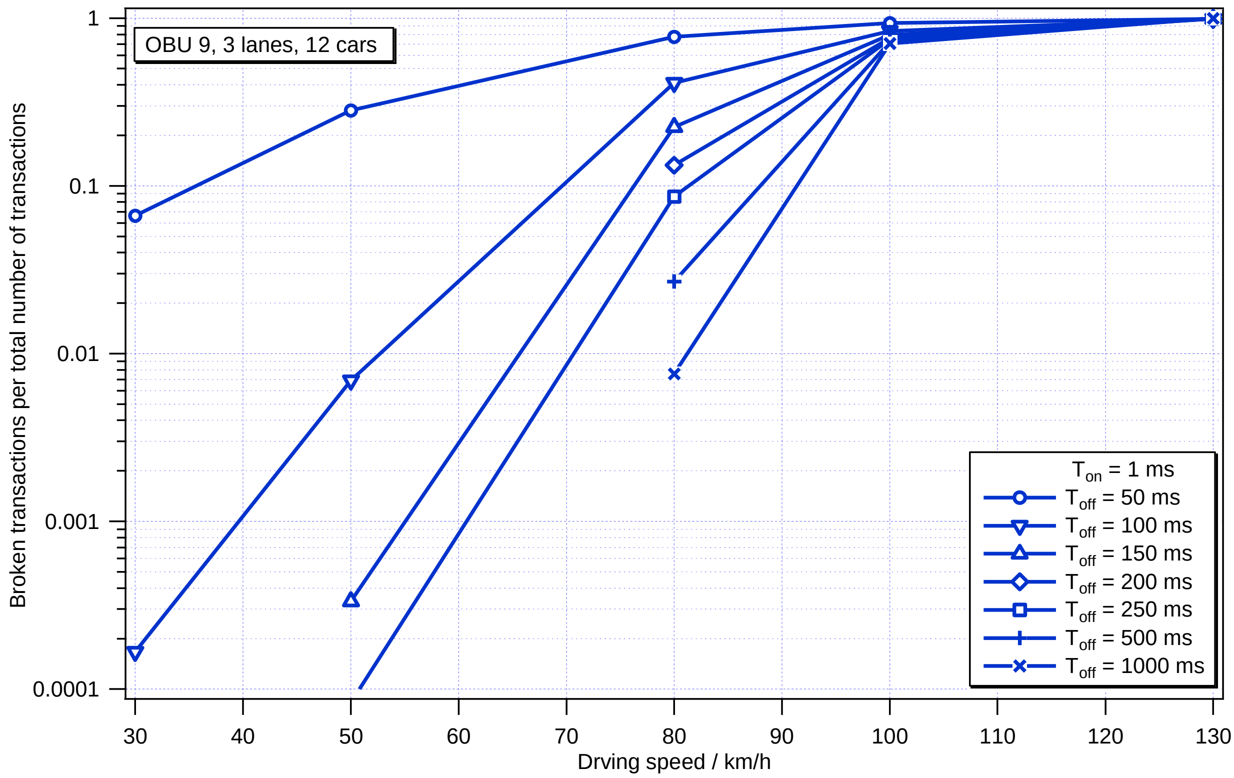


Figure C.24: Simulated ratio of potentially broken transactions at different speeds, caused by 3 interferers (cars), with an activity time T_{on} = 1 ms, to 12 concurrent CEN DSRC transactions with OBU9

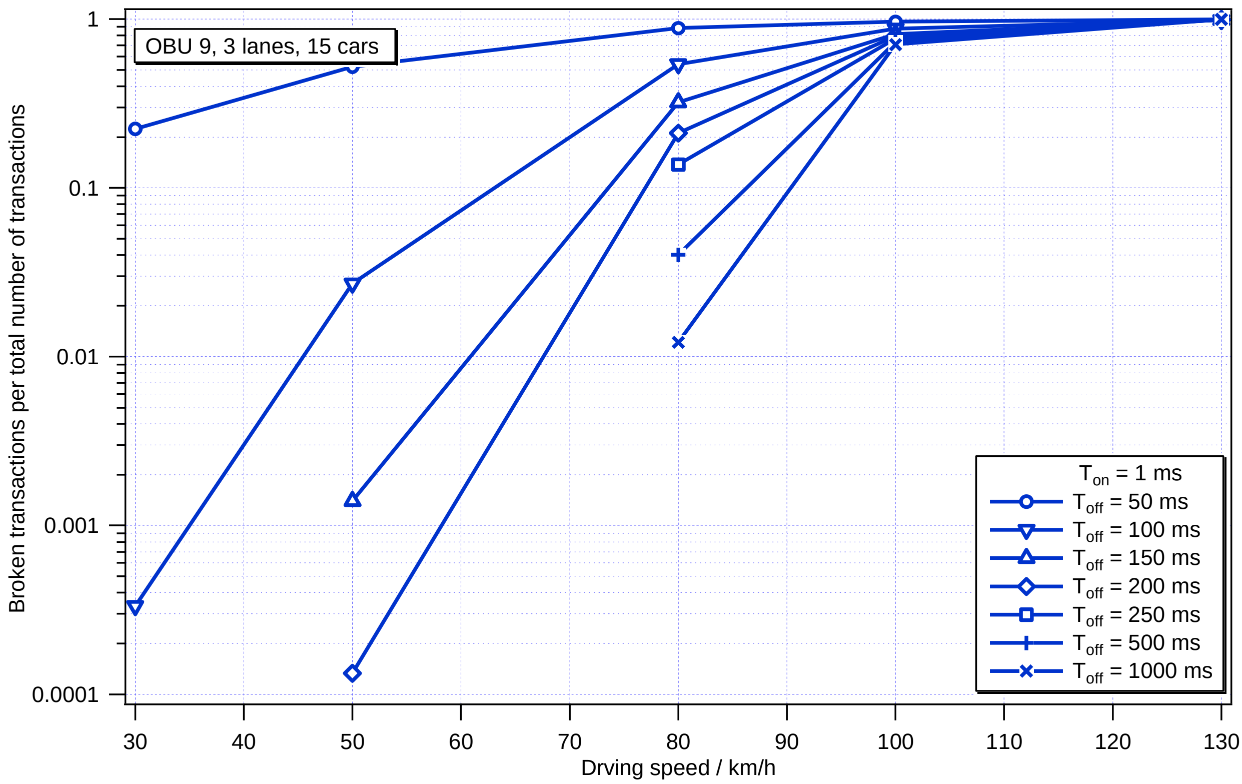


Figure C.25: Simulated ratio of potentially broken transactions at different speeds, caused by 15 interferers (cars), with an activity time T_{on} = 1 ms, to 3 concurrent CEN DSRC transactions with OBU9

Annex D: Bibliography

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NOTE: Available at http://docbox.etsi.org/Workshop/2011/201107_ITSG5_DSRC/03-Hjelmare-Coexistence_plugtest_CEN_DSRC.pdf.

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History

Document history		
V1.1.1	November 2012	Publication