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Mitigation techniques to avoid harmful interference between equipment compliant with ES 200 674-1 and ITS operating in the 5 GHz frequency range;
Evaluation of mitigation methods and techniques

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Foreword

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

Modal verbs terminology

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Executive summary

The present document is about mitigation techniques to avoid or lower harmful interference of ITS radio transmitters operating in the 5,9 GHz band upon 5,8 GHz backscatter communication systems used for e.g. electronic fee collection.

The present document comprises the evaluation of mitigation techniques specified in ETSI TS 102 792 [i.7] and their applicability for the High Data Rate - DSRC (HDR-DSRC) technology standardized by UNINFO in Italy and by ETSI ES 200 674-1 [i.1] used for road tolling.

As a global result it can be concluded that the mitigation techniques standardized in [i.7] for the CEN-DSRC technology (also referred to as Medium Data Rate - DSRC (MDR-DSRC), and recently named TTT DSRC as the term to be used in the future) are sufficient to avoid harmful interference to HDR-DSRC.

In order to perform the tests of which the results are reported in the present document, off-the-shelf equipment was used and no further calibration was performed. The transmit power of the ITS signal in the 5,9 GHz band could be tuned from 10 dBm EIRP to 23 dBm EIRP. The length of the ITS signals in terms of number of bytes could be adjusted within the limits allowed by this technology. The message repetition interval was set to either 10 ms or 100 ms. The HDR-DSRC system was operated with a test application (echo message of adjustable length), applying normal operational radio parameter settings (these could not be changed).

The performed measurements were compared with a statistical model presented in Annex A of the present document, which allows concluding whether the HDR-DSRC downlink, or the uplink, or both links are interfered. The performance results for the various test configurations with a single interferer and multiple interferers, both conducted in an anechoic chamber and in a real road environment, indicate that harmful interference is only on the HDR-DSRC downlink.

Coexistence scenarios were identified for HDR-DSRC, i.e. technical limits to mitigate harmful interference are:

- The ITS-SUs upper TX power limit is 14 dBm EIRP.
- The lower distance limit between a HDR-DSRC OBU and an ITS-M5 interferer transmitting with 23 dBm EIRP is 5 m.
- The ITS-M5 repetition interval of 100 ms is not resulting in harmful interference.

Introduction

With the birth of communications in the 5 GHz bands [i.2], [i.3], [i.4] for Intelligent Transport Systems (ITS) on the basis of the ITS station and communication architecture specified in [i.6] and [i.5] potential harmful interference caused by ITS equipment installed in vehicles on Electronic Fee Collection (EFC) and Electronic Toll Collection (ETC) installations (toll plazas) became obvious. Two major standardized Dedicated Short Range Communication (DSRC) technologies are used in Europe and other regions for EFC/ETC and other road transport related services, i.e. the CEN-DSRC technology standardized by CEN (also referred to as TTT-DSRC according to CEPT decision) and by ETSI in the European harmonised multi part standard ETSI EN 300 674-2-1 [i.11], ETSI EN 300 674-2-2 [i.12], and the High Data Rate - DSRC (HDR-DSRC) technology standardized by UNINFO in Italy and by ETSI ES 200 674-1 [i.1].

Both DSRC technologies operate in the same band at 5,8 GHz. Initial interference tests and simulations were performed for MDR-DSRC [i.8], and resulted in mitigation techniques standardized in [i.7]. These mitigation techniques were taken as basis for further investigations on HDR-DSRC.

The present document:

- complements [i.8] by presenting results of investigations on interference of 5,9 GHz ITS communications on the HDR-DSRC systems;
- recommends mitigation techniques with reference to [i.7]; and
- suggests running of an ETSI plug test dedicated to HDR-DSRC.

1 Scope

The present document reports about test executions and results of tests performed with equipment compliant with ETSI ES 200 674-1 [i.1] (referred to as HDR-DSRC or CEN-DSRC) and equipment compliant with ETSI EN 302 663 [i.4] operating in the 5 GHz frequency band (referred to as ITS-G5 or ITS-M5). The purposes of the tests are to identify potential interference of ITS-G5 emissions on the HDR-DSRC communications used e.g. for electronic road tolling, and the evaluation of mitigation techniques specified in ETSI TS 102 792 [i.7].

2 References

2.1 Normative references

Normative references are not applicable in the present document.

2.2 Informative references

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

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

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

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

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

[i.3] ISO 21215: "Intelligent transport systems -- Communications access for land mobiles (CALM) -- M5".

[i.4] ETSI EN 302 663 (V1.2.1) (07-2013): "Intelligent Transport Systems (ITS); Access layer specification for Intelligent Transport Systems operating in the 5 GHz frequency band".

[i.5] ETSI EN 302 665 (V1.1.1) (09-2010): "Intelligent Transport Systems (ITS); Communications Architecture".

[i.6] ISO 21217 (2014): "Intelligent transport systems -- Communications Access for Land Mobiles (CALM) -- Architecture".

[i.7] ETSI TS 102 792 (V1.2.1) (06-2015): "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 TR 102 960 (V1.1.1) (11-2012): "Intelligent Transport Systems (ITS); Mitigation techniques to avoid interference between European CEN Dedicated Short Range Communication (RTTT DSRC) equipment and Intelligent Transport Systems (ITS) operating in the 5 GHz frequency range; Evaluation of mitigation methods and techniques".

[i.9] Commsignia: "OB2-M/ITS-RS2-M User Manual"; version: V1.7.5-b12, 3 (March 2015).

[i.10] Narda Safety Test Solutions: "SRM 3006® Selective Radiation Meter Operating Manual".

[i.11] ETSI EN 300 674-2-1 (V2.1.1) (11-2016): "Transport and Traffic Telematics (TTT); Dedicated Short Range Communication (DSRC) transmission equipment (500 kbit/s / 250 kbit/s) operating in the 5 795 MHz to 5 815 MHz frequency band; Part 2: Harmonised Standard covering the essential requirements of article 3.2 of the Directive 2014/53/EU; Sub-part 1: Road Side Units (RSU)".

[i.12] ETSI EN 300 674-2-2 (V2.1.1) (11-2016): "Transport and Traffic Telematics (TTT); Dedicated Short Range Communication (DSRC) transmission equipment (500 kbit/s / 250 kbit/s) operating in the 5 795 MHz to 5 815 MHz frequency band; Part 2: Harmonised standard covering the essential requirements of article 3.2 of Directive 2014/53/EU; Sub-part 2: On-Board Units (OBU)".

3 Definitions, symbols and abbreviations

3.1 Definitions

For the purposes of the present document, the terms and definitions given in ETSI ES 200 674-1 [i.1] and the following apply:

ITS-G5: access technology to be used in frequency bands dedicated for European Intelligent Transport System (ITS)

NOTE: Details of compliance are specified in ETSI EN 302 663 [i.4] and ISO 21215 [i.3].

ITS-M5: communications technology operating in the 5 GHz bands allocated for ITS compliant with IEEE 802.11 [i.2]

NOTE: Details of compliance are specified in ETSI EN 302 663 [i.4] and ISO 21215 [i.3].

3.2 Symbols

For the purposes of the present document, the symbols given in ETSI ES 200 674-1 [i.1] and the following apply:

f_c	HDR DSRC downlink centre frequency
$f_{c,ITS}$	ITS-M5 centre frequency
G_{OBU}	Gain of the HDR-DSRC OBU antenna in bore-sight direction
G_{RSU}	Gain of the HDR-DSRC RSU antenna in bore-sight direction
N_{bundle}	Number of HDR-DSRC test signals (ECHO.request) in a test bundle
$N_{success}$	Number of successfully received HDR-DSRC test signals (ECHO.response) in a test bundle
P_{loss}	Probability of lost HDR-DSRC test signals
$P_{overlap}$	Probability of an overlap of ITS test signal with interfered HDR-DSRC test signal
$P_{success}$	Probability of successfully received HDR-DSRC test signals
T_{d1}	Duration of interfered HDR-DSRC test signal
T_{d2}	Duration of interfering ITS test signal
T_{d1d}	Duration of HDR-DSRC downlink test signal
T_{d1u}	Duration of HDR-DSRC uplink test signal
T_{p1}	Repetition period of HDR-DSRC test signal
T_{p2}	Repetition period of ITS test signal

3.3 Abbreviations

For the purposes of the present document, the abbreviations given in ETSI ES 200 674-1 [i.1] and the following apply:

AM	Amplitude Modulation
CEN	European Committee for Standardization
CEPT	Conférence Européenne des Administrations des Postes et des Télécommunications
CTI	Centre for Testing and Interoperability
DC	Direct Current
DSRC	Dedicated Short Range Communication
EFC	Electronic Fee Collection
EIRP	Effective Isotropic Radiated Power
ETC	Electronic Toll Collection

FSK	Frequency Shift Keying
HDR	High Data Rate
HDR-DSRC	High Data Rate - DSRC
ISO	International Organization for Standardization
ITS	Intelligent Transport Systems
ITS-SU	ITS Station Unit
ITS-SU	ITS Station Unit
JRC	Joint Research Centre (of the European Commission)
LPDU	Link Protocol Data Unit
MAC	Medium Access Control
MDR-DSRC	Medium Data Rate-DSRC
MIB	Management Information Base
OBU	On Board Unit
OCB	Outside the Context of a BSS
OFDM	Orthogonal Frequency Division Multiplexing
PSK	Phase Shift Keying
RF	Radio Frequency
RSU	Road Side Unit
SRM	Selective Radiation Meter
TTT DSRC	Traffic Transport Telematics DSRC
TTT	Transport and Traffic Telematics
TX	Transmit

4 HDR-DSRC

4.1 Operational characteristics

Typical HDR-DSRC EFC/ETC installations are:

- Free-flow tolling installations with up to about 6 parallel lanes (typical 3 to 4 lanes in each traffic direction).
- Toll plazas with automatic barriers with up to about 40 parallel lanes (typical around 10 to 20 lanes in each traffic direction).

The geometrical coordinate system of HDR-DSRC installations used in the present document is depicted in Figure 1 and Figure 2.

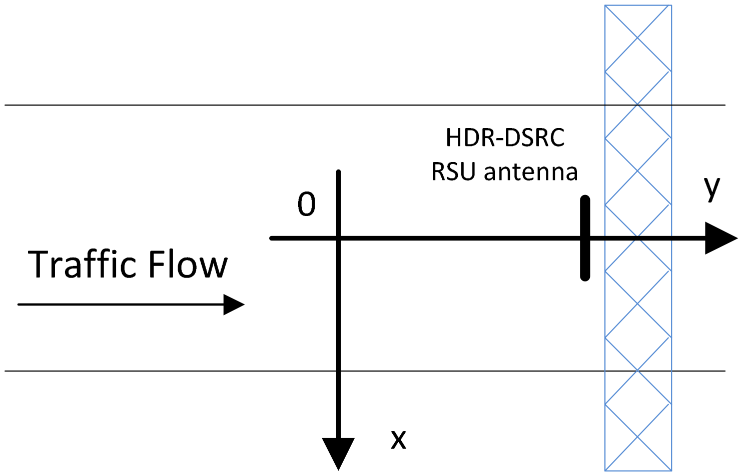

Figure 1: HDR-DSRC installation - top view

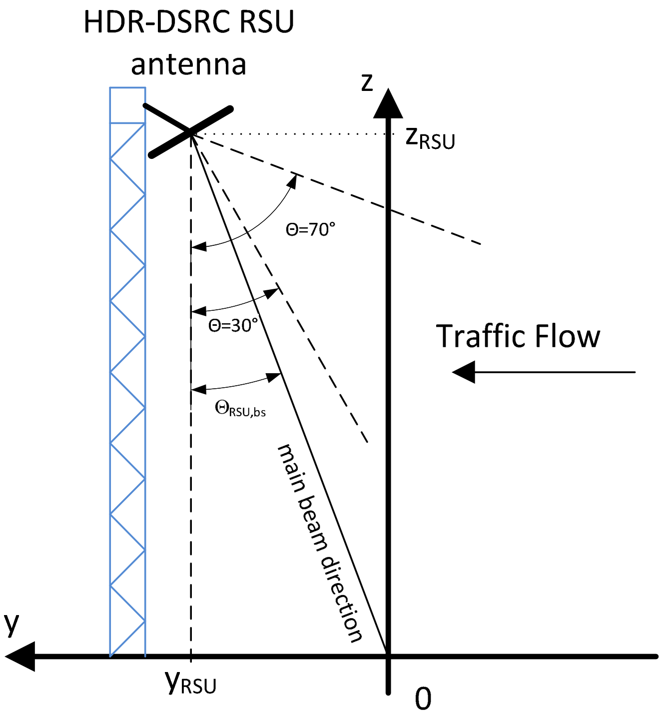

Figure 2: HDR-DSRC installation - side view

The position {x=0, y=0, z=0} is the intersection of the main beam of the HDR-DSRC RSU antenna with the lane. The centre of the HDR-DSRC RSU antenna is at the position {$x=x_{RSU}=0$, $y=y_{RSU}$, $z=z_{RSU}$}.The main beam direction of the HDR-DSRC RSU antenna is given by the angle $\Theta=\Theta_{RSU,bs}$. Limits of radiated power as a function of Θ are presented in Table 1. The position of a HDR-DSRC OBU (not shown in the above figures) is {$x=x_{OBU}$, $y=y_{OBU}$, $z=z_{OBU}$}.

A typical installation of HDR-DSRC RSUs is presented in Figure 3. The angle $\Theta_{RSU,bs}$ is very small and thus the hot spot on the lane is very limited in length (y-axis in Figures 1 and 2).

Figure 3: Typical HDR-DSRC RSU installation

4.2 Technical characteristics

4.2.1 Roadside unit

Characteristics of HDR-DSRC RSUs are presented in Table 1.

Table 1: Parameters of a typical HDR-DSRC RSU

HDR-DSRC RSU RF parameter	Value	Comment
Receiver bandwidth	(0,7 MHz + 0,288 MHz) × 2 = 1,976 MHz	FSK frequency deviation (0,7 MHz) plus symbol rate bandwidth considering the Manchester coding scheme and the uplink symbol rate of 288 kbit/s.
Receiver sensitivity	≤ -92 dBm	
Receiver centre frequency	f_c ± 10,7 MHz	
Antenna bore sight direction, see Figure 2	$\Theta_{RSU,bs}$	Depends on installation.
Antenna polarization	Vertical linear	
Antenna cross polarization	> 20 dB	In boresight.
	≥ 10 dB	-3 dB area.
Transmitter bandwidth	f_c ± 1,842 MHz	Considering the Manchester coding scheme and the symbol rate of 1 842 kbit/s.
Transmitter angular EIRP mask Θ is the angle relative to a vector perpendicular to the road surface, pointing downwards, see Figure 2	≤ +39 dBm	0° ≤ Θ ≤ 30°.
	≤ +33 dBm	30° < Θ ≤ 50°.
	≤ +23 dBm	50° < Θ ≤ 70°.
	≤ +15 dBm	Θ > 70°.
Transmitter carrier centre frequency f_c	5,8 GHz, 5,81 GHz	5,81 GHz is an optional centre frequency potentially used in the future for free-flow tolling.
Downlink modulation scheme	ASK-OOK	
Downlink data coding	Manchester	
Downlink bit rate	921 kbit/s	
Protection criterion (S/I) - co-channel rejection limit	6 dB	FSK, 2-PSK.

4.2.2 Onboard unit

Characteristics of HDR-DSRC OBUs are presented in Table 2.

Table 2: Parameters of a typical HDR-DSRC OBU

HDR-DSRC OBU RF parameter	Value	Comment
Wake-up sensitivity	≤ -40 dBm	Wake-up on a defined pattern.
Receiver sensitivity	≤ -40 dBm	Measured within the 35° border of a cone symmetrically around boresight direction as declared by the manufacturer.
Antenna bore sight direction	not directly specified in [i.1]	Depends on installation in vehicle.
Antenna cross polarization	> 10 dB	In boresight.
	≥ 6 dB	-3 dB area.
Antenna gain outside HDR-DSRC OBU active angle range	≤ G_{OBU} - 1,5 dB	
Antenna polarization	either vertical linear or left-hand circular	
Vehicle windscreen loss	3 dB	Depends on installation in vehicle.
Transmitter bandwidth	f_c ± (10,7 MHz + 0,7 MHz + 0,288 MHz) = f_c ± 11,688 MHz	See uplink modulation scheme, data encoding, and data rate. Same data sent simultaneously in both sidebands.
Transmitter maximum output power level, Single-sideband EIRP	< -14 dBm	Measured at the 35° border of a cone symmetrically around boresight direction, i.e. at the border of the -3 dB area.
Transmitter sub carrier centre frequencies	f_c ± 10,7 MHz	Sub-carrier @ 10,7 MHz FSK modulated with two tones ±0,7 MHz: Binary FSK (±700 kHz) on sub-carrier at 10,7 MHz.
Uplink modulation scheme	AM	On carrier.
Uplink data coding	Manchester	
Uplink bit rate Same data are sent simultaneously in both sidebands	144 kbit/s	

Figure 4 shows a worst case theoretical HDR-DSRC OBU antenna pattern compliant with the definition of the 3 dB area in ETSI ES 200 674-1 [i.1]. The figure is normalized to the antenna gain in bore-sight direction and shows the square-law attenuation as function of the opening angle Θ of the cone in the range zero degree (bore-sight) to 90°.

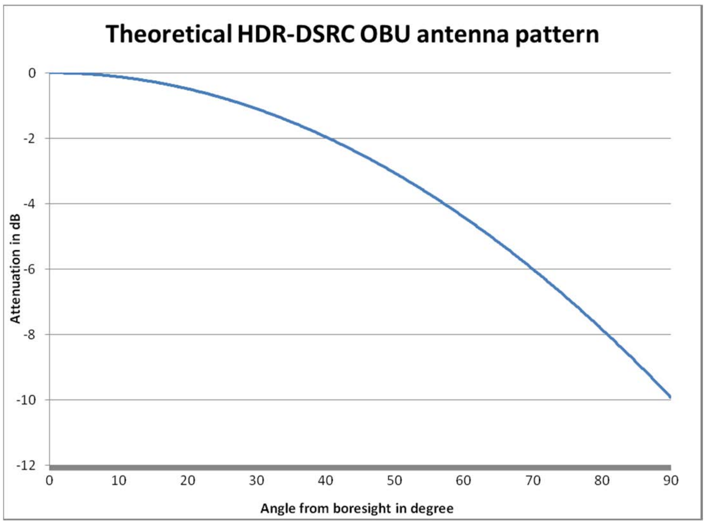

Figure 4: Worst case theoretical HDR-DSRC OBU antenna pattern compliant with ETSI ES 200 674-1 [i.1]

4.3 Protocol characteristics

All transmissions are in frames. A frame consists of a one octet start flag, a Link Protocol Data Unit (LPDU) field of variable length, a two octet frame check sequence, and a one octet stop flag. The total length of a frame in downlink and uplink communications is limited to 64 octets plus a number of zero bits inserted dependent on the data in order to avoid appearance of the flag pattern in between the start flag and stop flag.

In downlink communications, a wake-up signal with maximum duration of 2,36 ms may be sent by an HDR-DSRC RSU.

In the downlink and the uplink, communications will start with a preamble, followed by the frame described above. The size of a preamble is between 16 bits and 32 bits; this corresponds to a duration of 111 µs up to 222 µs at 144 kbit/s in the uplink, and 17,4 µs up to 34,8 µs at 921 kbit/s in the downlink.

The maximum downlink transmission time of a frame T_{dmax} (without wake-up header and preamble) is 590 µs. If an expected reply is not received or the frame received is invalid, the HDR-DSRC RSU may retransmit the same message after an interval of 10 ms ± 1 ms defined as polling time T_1. The downlink frame of maximum length with wake-up header is presented in Figure 5.

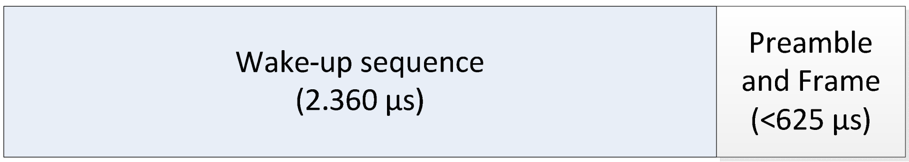

Figure 5: Downlink frame of maximum length with wake-up header

Within an unspecified link-turn-around time, an HDR-DSRC OBU responds to a correctly received frame. The maximum uplink transmission time T_{umax} is 3,8 ms.

4.4 Interference characteristics

Communication characteristics of interferers are standardized in ETSI EN 302 663 [i.4], based on IEEE 802.11 [i.2]:

- Orthogonal frequency division multiplexing (OFDM);
- MIB parameter dot11OCBActivated set to true, i.e operation "Outside of the context of a Basic Service set" (OCB);

with context details specified in ISO 21215 (ITS-M5) [i.3] and in ETSI EN 302 663 [i.4]. For further information, see the presentation of the test set-up in clause 5.2.1.

Potential interference from ITS-G5 / ITS-M5 on HDR-DSRC systems is threefold:

- Interference on downlink communications, i.e. communications from a High Data Rate DSRC Road Side Unit (HDR-DSRC RSU) to a High Data Rate DSRC On Board Unit (HDR-DSRC OBU) is interfered.
- Interference on uplink communications, i.e. communications from a an HDR-DSRC OBU to an HDR-DSRC RSU is interfered.
- Unwanted wake-up of an HDR-DSRC OBU.

NOTE: Unwanted wake-up of an HDR-DSRC OBU is not considered in the present document.

Interference on communications can happen only at time of transactions between an HDR-DSRC RSU and an HDR-DSRC OBU being present in the communication zone of the HDR-DSRC RSU. This allows for a statistical model predicting the worst case interference scenario (see Annex A).

5 Measurements

5.1 Test architecture

5.1.1 General approach

Having already the knowledge of interference on the MDR-DSRC [i.8], [i.7], initially major interest was in a general understanding of interference on the HDR-DSRC for typical scenarios with typical equipment in real environment, rather than a more scientific investigation.

Commercial ITS-SUs operating at 5,9 GHz with roof-top antennas to generate potentially interfering signals, and typical installations of HDR-DSRC and ITS equipment in a car (see Figures 6 and 7), were used to perform tests on a test toll plaza (see Figure 8) of the road operator Autostrade per l'Italia in Firenze, Italy.

Figure 6: HDR-DSRC OBU installed in vehicle

Figure 7: ITS-SU roof-top antenna installed in vehicle

Figure 8: Test toll plaza in Firenze

With this simple self-interferer scenario, it was impossible to measure significant interference.

In further tests, the HDR-DSRC OBU and one or several ITS roof-top antennas were installed on tripods such that the shielding capability of the passenger cabin of a car no more applied. These further tests were initially performed in Firenze on the same test toll plaza, but in order to improve the measurements and to be independent of weather conditions, finally tests were performed in an anechoic chamber at the JRC in Ispra.

Figure 9 shows a test set-up with an ITS roof-top antenna in between an HDR-DSRC RSU and an HDR-DSRC OBU. Figures 10 and 11 show details of this test set-up at JRC, i.e. test antennas installed close to HDR-DSRC RSU and HDR-DSRC OBU connected to spectrum analysers. The test antennas are used to measure the far-field signal of the respective other unit that is not visible on the figures.

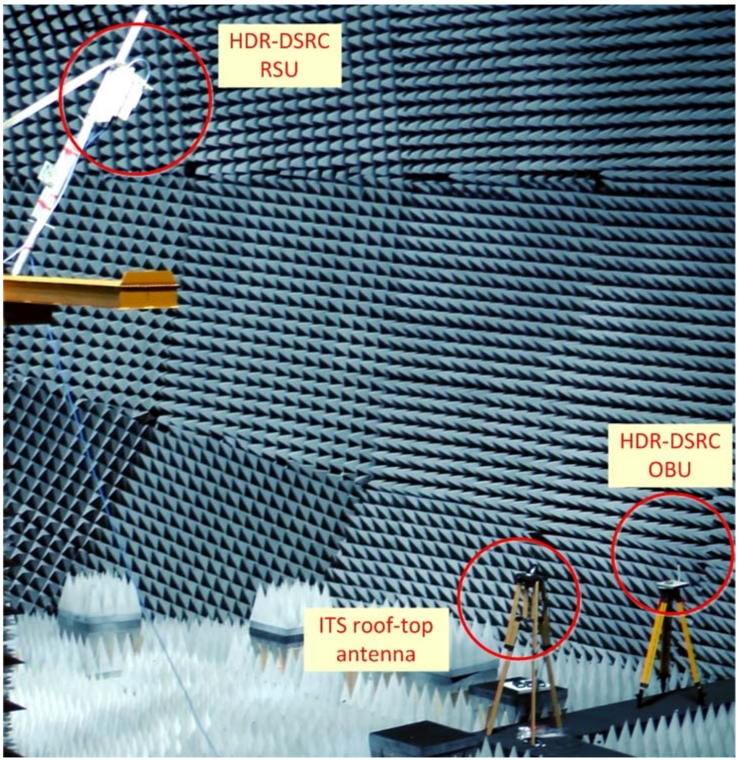

Figure 9: Test set-up with one ITS roof-top antenna in-between HDR-DSRC OBU and HDR-DSRC RSU

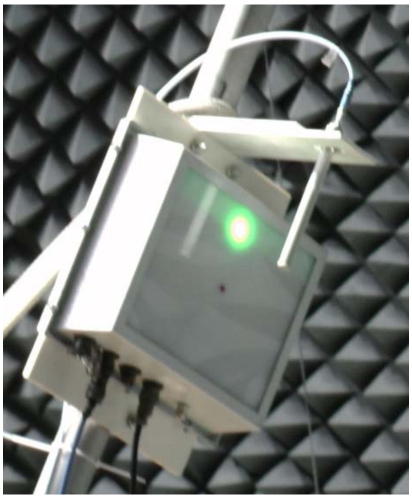

Figure 10: Test antenna close to HDR-DSRC RSU, measuring the OBU and ITS-SU spectrum

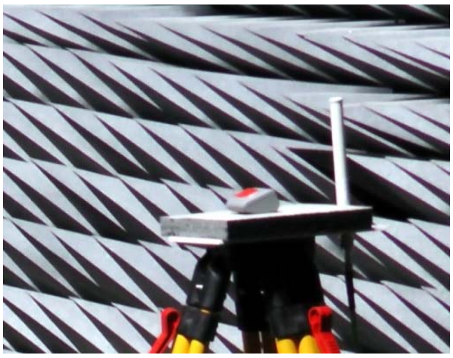

Figure 11: Test antenna close to HDR-DSRC OBU, measuring the RSU spectrum

Final tests were performed on a test site from ESF GmbH in Germany presented in Figure 12. Tests performed at this test site aimed at validating the results gathered at the JRC.

Figure 12: Test site with HDR-DSRC reader on a gantry, HDR-DSRC OBU on a tripod, and ITS-G5 rooftop antenna on a car in front of the HDR-DSRC OBU

5.1.2 Test signals

5.1.2.1 ITS test signal

The interfering ITS test signal sent by the ITS-SU transmitter is a continuous sequence of ITS-M5 packets with 2 300 octets of random data at defined repetition intervals T_{p2}, see also Table 3. The data rate is the default rate for a given transmitter centre frequency.

NOTE: The repetition interval T_{p2} is the scheduled interval, see Figure A.1. The real situation in the communication channel depends on the processing at the MAC layer, and other nearby ITS-M5 transmitters.

5.1.2.2 HDR-DSRC test signal

The HDR-DSRC test signal sent by the HDR-DSRC RSU in the downlink is an ECHO.request signal of maximum length, i.e. 64 octets, see also Table 3. An HDR-DSRC OBU acknowledges reception of an ECHO.request signal with an ECHO.response signal of same length.

The repetition period T_{p1} of ECHO.request signals (see Figure A.1) is set to 10 ms, which is equal to the maximum wait time for ECHO.responses. The retransmission feature of HDR-DSRC is not used in the ECHO service.

5.1.3 Test procedure

In each test run, a total of N_{bundle} = 5 000 ECHO.request signals are sent by the HDR-DSRC RSU. Upon successful reception of an ECHO.request signal, an HDR-DSRC OBU acknowledges it with an ECHO.response signal of same length. The HDR-DSRC RSU waits for the maximum allowed time for the ECHO.response. If the ECHO.response is received within the expected time, then the next ECHO.request is sent after the repetition period T_{p1} expired. Otherwise upon expiration of the repetition period T_{p1}, the HDR-DSRC RSU notes failure of reception of the expected ECHO.response, and sends the next ECHO.request. Finally at the end of each test run the ratio:

$$P_{success} = \frac{N_{success}}{N_{bundle}}$$

of correctly received ECHO.response signals $N_{success}$ over N_{bundle} is calculated.

Interference basically can happen:

- only on the uplink of duration T_{d1u}; or
- only on the downlink of duration T_{d1d}; or
- on both links.

Formula A.10 of the statistical model, presented in Annex A, allows calculating the lower bound of $P_{success}$ for these three cases as presented in Table 3.

Table 3: Expected HDR-DSRC performance success rates

$P_{success}$	$T_{d1} = T_{d1d}$ = 625 µs	$T_{d1} = T_{d1u}$ = 3,8 ms	$T_{d1} = T_{d1d} + T_{d1u}$ = 4,425 ms
T_{p2} = 10 ms	63,1 %	31,3 %	25,1 %
T_{p2} = 100 ms	96,3 %	93,1 %	92,5 %
NOTE: The duration of the interfering ITS signal with 2 300 octets random data is about T_{d2} = 3,07 ms (see Figure A.1).			

5.1.4 Test scenarios

- Real operational environment, toll plaza (see Figures 6, 7 and 8).
- Anechoic chamber with antennas on tripods:
  - single interferer at various locations (see Figures 9 and 17);
  - multiple interferers at various locations (see Figure 26).
- Test environment, test site (see Figure 12), with single interferer in front of the HDR-DSRC OBU.

5.2 Evaluation of test equipment

5.2.1 ITS station units

ITS 5,9 GHz test signals were produced with commercially available equipment, namely the *ITS-RS2-M* ITS-SU from Commsignia [i.9] (see Figure 13).

Figure 13: ITS-RS2-M ITS-SU from Commsignia [i.9]

The ITS-G5 spectrum of the *ITS-RS2-M* ITS-SU was measured at the University of Ulm, see Figures 14 and 15. The *ITS-RS2-M* ITS-SU was connected to a Rohde & Schwarz Signal Source Analyzer FSUP8 (DC - 8 GHz) by cable. The resolution bandwidth was set to 1 kHz. The *ITS-RS2-M* was set to transmit with 10 dBm EIRP using the roof-top antenna. However the measurement was performed without antenna, directly connecting the antenna port of *ITS-RS2-M* to the spectrum analyzer.

Figure 14, as an example, shows the spectrum of the *ITS-RS2-M* ITS-SU tuned to the centre frequency of 5,9 GHz symmetrically around the centre frequency with transmit power set to 10 dBm EIRP. The difference between the expected power level of -30 dBm/kHz is due to the missing antenna gain of the rooftop antenna.

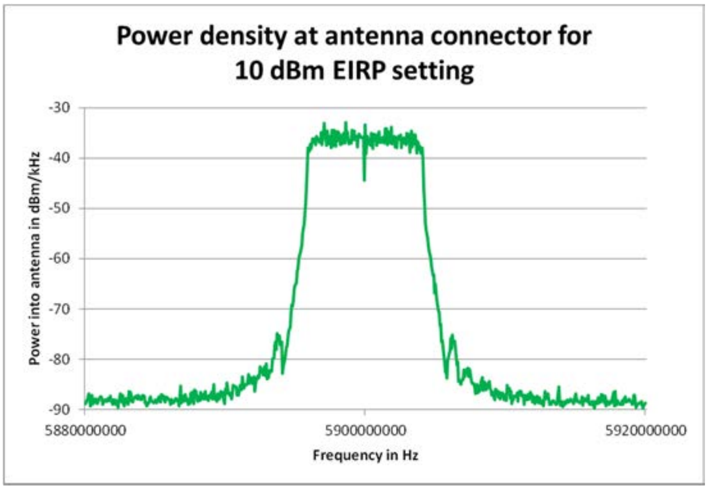

Figure 14: ITS-G5 spectrum in the range 5,88 GHz to 5,92 GHz with TX centre frequency set to 5,9 GHz - measured at the antenna port

Figure 15, as an example, shows the spectrum of the *ITS-RS2-M* ITS-SU tuned to the centre frequency of 5,9 GHz symmetrically around the centre frequency of the HDR DSRC system (5,8 GHz) with transmit power set to 10 dBm EIRP (green), and transmitter being switched off (black). No significant difference between 10 dBm EIRP TX power and "TX switched off" could be measured.

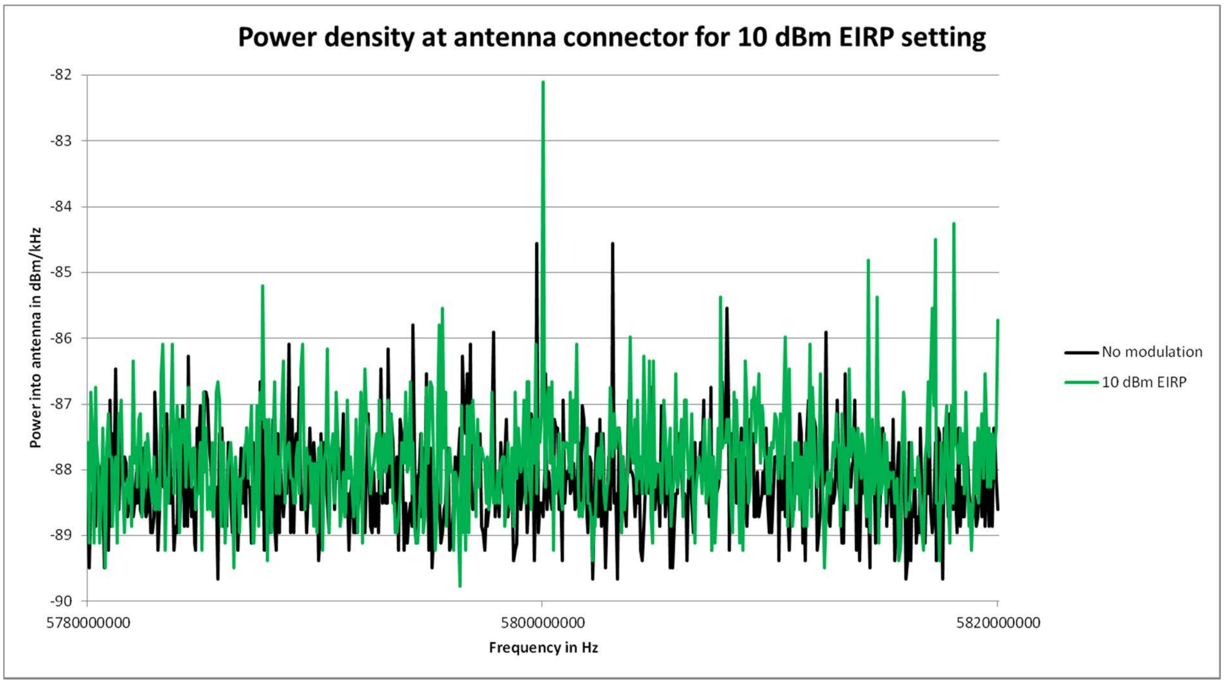

Figure 15: ITS-G5 spectrum in the range 5,78 GHz to 5,82 GHz with TX centre frequency set to 5,9 GHz

5.2.2 Equipment at the German test site

At the test site in Germany, radio spectra were measured using a portable selective radiation meter SRM 3006 from Narda Safety Test Solutions [i.10] (see Figure 16). These measurements were performed to validate presence or absence of the expected signals.

Figure 16: SRM 3006 with antenna

5.3 Tests

5.3.1 No interference

With no interference from an ITS-SU, a success rate of 100 % was expected. However, in most cases this was not achieved. The reason why one or several ECHO.response messages out of the whole test bundle of 5 000 trials were not received can be assumed as a normal tolerated malfunction of the involved devices that stays within the tolerance limits. The normal erasure rate is about < 5 transactions out of 5 000 transactions.

5.3.2 Single interferer

5.3.2.1 Tests on toll plaza

Originally it was assumed that, due to the shielding caused by the roof of the test vehicle (see Figure 7), interference on the downlink is negligible. As a matter of fact, no significant interference could be observed in these tests. Based on the original assumption and the observation in the tests, it was concluded that interfering signals likely will be effective mainly on the downlink, e.g. caused by ITS-SUs in front of the HDR-DSRC OBU. This conclusion was confirmed by interferers installed on tripods around the HDR-DSRC OBU with line-of-sight visibility.

5.3.2.2 Tests in anechoic chamber

5.3.2.2.1 Test set-up A

Test set-up A is given by a typical off-the-shelf HDR-DSRC OBU installed in-between the HDR-DSRC RSU and the ITS-SU roof-top antenna (see clause 5.2.1). This single-interferer test set-up is illustrated in Figure 17, operated with default values. The centre frequency of the ITS-SU transmitter was set to $f_{c,ITS}$ = 5 860 MHz. The distances between the three antennas were identified. The orientation of the HDR-DSRC antenna (angle $\Theta_{RSU,bs}$) was not according to the typical installation in a toll plaza; a typical installation with $\Theta_{RSU,bs}$ close to zero is presented in Figure 3. It was verified by a reference measurement that the HDR-DSRC OBU still is inside the HDR-DSRC communication zone, however the precise position relative to the HDR-DSRC main beam direction (see Figure 2) was not measured.

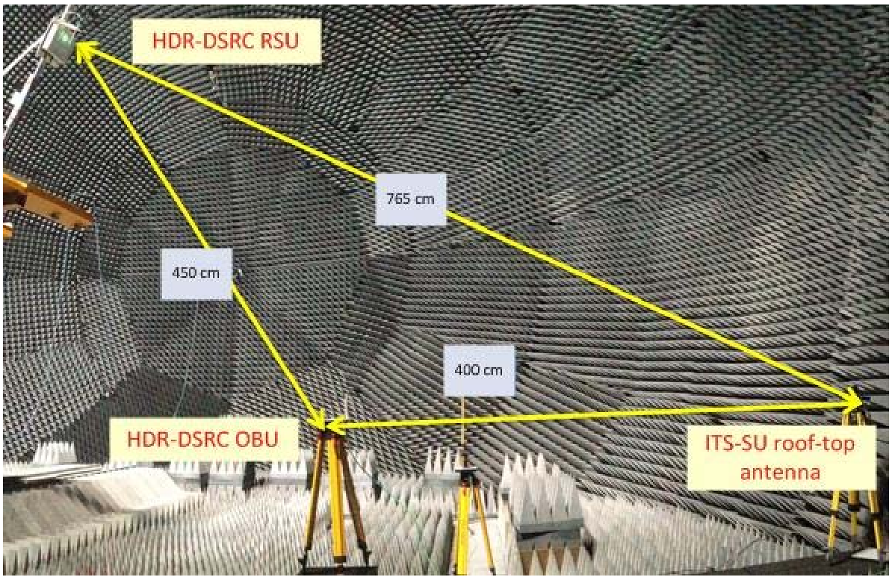

Figure 17: Test set-up A

Table 4 shows the ITS-SU TX power setting, the repetition interval T_{p2} setting, and the measured results.

Table 4: Single-interferer tests - test set-up A

Test run #	Repetition interval T_{p2}	Interferer EIRP	Success rate
1	10 ms	23 dBm	62,44 %
6	10 ms	18 dBm	65,02 %
7	10 ms	17 dBm	71,73 %
5	10 ms	16 dBm	91,31 %
4	10 ms	14 dBm	99,68 %
3	10 ms	12 dBm	99,96 %
2	10 ms	10 dBm	99,96 %
10	100 ms	23 dBm	96,26 %
9	100 ms	18 dBm	96,31 %
8	100 ms	17 dBm	96,5 %

The results are as predicted by the statistical model for downlink interference (see Annex A and Table 3). The measured success rate is presented in Figure 18 as a function of the TX EIRP in dBm.

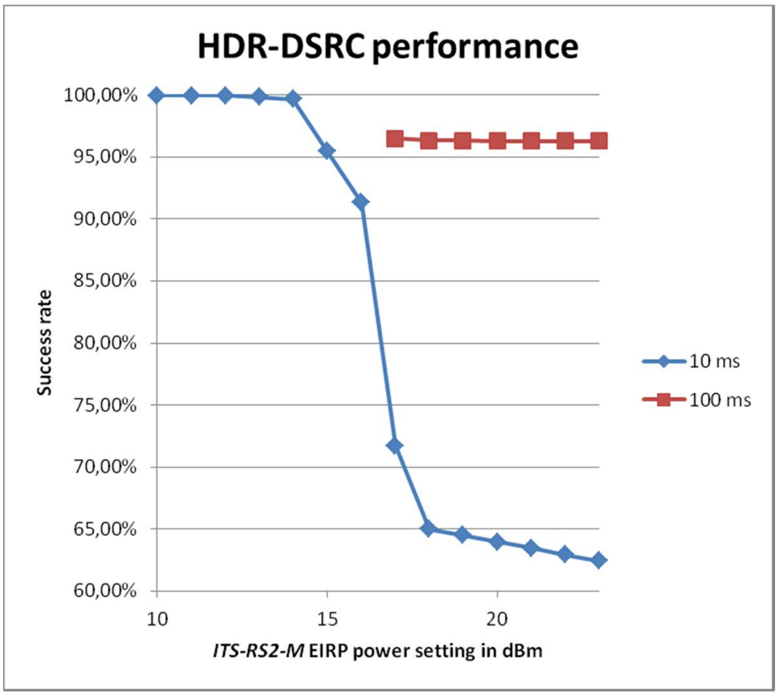

Figure 18: Test set-up A - Success rate versus TX EIRP in dBm

5.3.2.2.2 Test set-up B

Test set-up B is given by an ITS-SU roof-top antenna (see clause 5.2.1) installed in-between the HDR-DSRC RSU, operated with default values, and the typical off-the-shelf HDR-DSRC OBU. This single-interferer test set-up is illustrated in Figure 9. The centre frequency of the ITS-SU transmitter was set to $f_{c,ITS}$ = 5 860 MHz, and to $f_{c,ITS}$ = 5 900 MHz. The repetition interval T_{p2} was set to 10 ms. The distances between the three antennas were identified. The orientation of the HDR-DSRC antenna (angle $\Theta_{RSU,bs}$) was not according to the typical installation in a toll plaza; a typical installation is presented in Figure 3. It was verified by a reference measurement that the HDR-DSRC OBU is inside the HDR-DSRC communication zone, however the precise position relative to the HDR-DSRC main beam direction, see Figure 2, was not measured.

Table 5 shows the ITS-SU TX power setting, the centre frequency $f_{c,ITS}$, and the measured results.

Table 5: Single-interferer tests - test set-up B

Test run #	Centre frequency $f_{c,ITS}$	interferer EIRP	Success rate
1	5 860 MHz	23 dBm	68,72 %
5	5 860 MHz	19 dBm	62,57 %
6	5 860 MHz	18 dBm	62,96 %
7	5 860 MHz	17 dBm	64,23 %
4	5 860 MHz	16 dBm	98,92 %
8	5 860 MHz	15 dBm	99,31 %
3	5 860 MHz	13 dBm	99,97 %
2	5 860 MHz	10 dBm	99,98 %
13	5 900 MHz	20 dBm	63,15 %
12	5 900 MHz	19 dBm	70,19 %
11	5 900 MHz	18 dBm	94,04 %
10	5 900 MHz	17 dBm	99,65 %
9	5 900 MHz	15 dBm	99,97 %
14	5 900 MHz	10 dBm	99,98 %

The results are as predicted by the statistical model for downlink interference (see Annex A and Table 3). Interference at 5 860 MHz is higher than interference at 5 900 MHz, as expected. The measured success rate is presented in Figure 18 as a function of the TX EIRP in dBm.

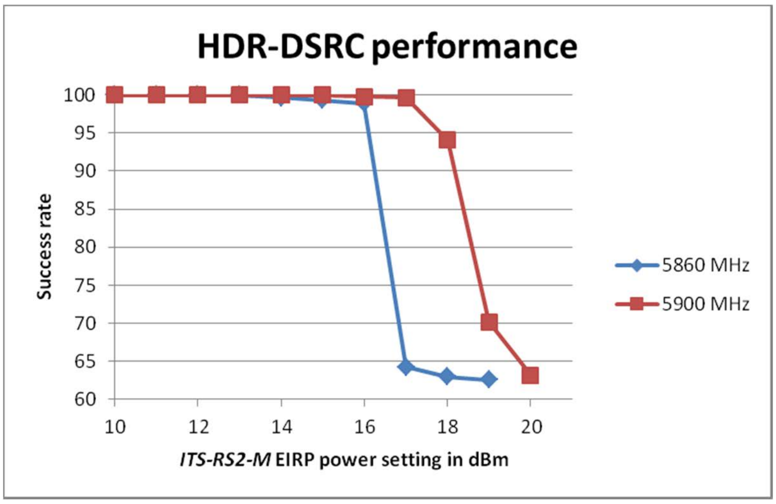

Figure 19: Test set-up B - Success rate versus TX EIRP in dBm

5.3.2.3 Final tests on toll site

This final test set-up is given by an HDR-DSRC OBU installed inside the communication zone of an HDR-DSRC RSU behind an ITS-SU roof-top antenna (see clause 5.2.1). This single-interferer test set-up is illustrated in Figure 20.

The HDR-DSRC RSU antenna is installed on the gantry with x_{RSU} = 0 m, z_{RSU} = 5,5 m, Θ_{RSU} = 30°.

The HDR-DSRC OBU is installed on a tripod with x_{OBU} = 0 m, z_{OBU} = 1,5 m and y_{OBU} such that the OBU is just inside the communication zone with 100 % success rate.

The ITS-SU roof-top antenna is installed at $x_{ITS\text{-}SU}$ = 0 m, $z_{ITS\text{-}SU}$ = 1,8 m with variable distance $d_{ITS\text{-}SU\text{ - }OBU}$ to the OBU.

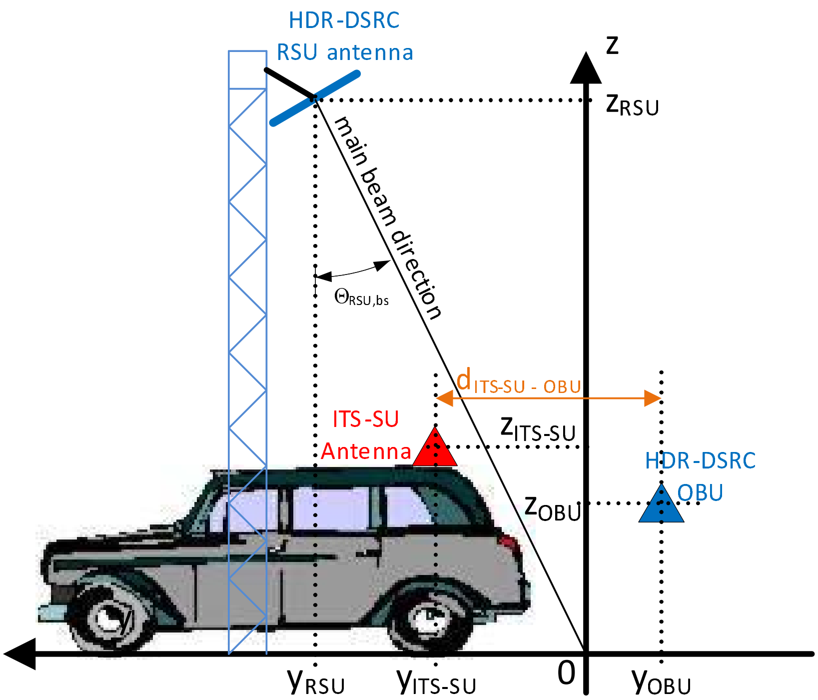

Figure 20: Test set-up

The centre frequency of the ITS-SU transmitter was set to $f_{c,ITS}$ = 5 900 MHz and 5 860 MHz.

The repetition interval of the interfering ITS test signal was set to 10 ms, with a size of the ITS-M5 packets set to 2 300 octets (see clause 5.1.2.1). The HDR-DSRC test signal was as specified in clause 5.1.2.2.

Table 6 shows the ITS-SU TX power settings, distance $d_{ITS\text{-}SU\text{ - }OBU}$, ITS-M5 centre frequency, and the measured results for the setup illustrated in Figure 20.

Table 6: Tests at ITS-M5 centre frequency of 5 860 MHz and 5 900 MHz

Distance $d_{ITS\text{-}SU\text{ - }OBU}$ / m	Interferer EIRP / dBm	Success rate / %	
		@ 5 860 MHz	@ 5 900 MHz
2,5	23	62,49	62,54
2,5	21	-	64,21
2,5	20	62,78	69,47
2,5	19	-	94,31
2,5	18	65,67	99,13
2,5	17	97,03	-
2,5	16	99,95	-
3	23	62,47	65,68
3	22	-	70,42
3	21	-	84,95
3	20	62,76	96,47
3	19	-	99,96
3	18	69,37	-
3	17	98,65	-
3	16	99,88	-
3,5	23	62,48	96,56
3,5	22	-	99,26
3,5	21	-	99,82
3,5	20	62,48	-
3,5	18	64,14	-
3,5	17	78,92	-
3,5	16	94,82	-
3,5	15	99,73	-
4	23	64,31	62,52
4	20	82,53	87,13
4	19	81,35	96,58
4	18	96,74	98,87
4	17	99,8	-
4,5	23	100	100

The results are as predicted by the statistical model for downlink interference (see Annex A and Table 3). Lessons learnt are:

- Wrong alignment of HDR-DSRC OBU with linear polarization has a severe impact on the test result.
- The actual battery status of the OBU, when below a certain level, has a severe impact on the test result. It has to be noted that for each test run several thousands of messages were exchanged, which in fact; simulated a usage of the OBU for several years.
- Major interference is on the downlink only, as success rate never goes well below 63 %.
- Interference is negligible below an ITS TX power level of about 15 dBm.
- For an interferer EIRP of up to 23 dBm the interference is negligible at distances further away than 4,5 m.

Tests were not repeated at a repetition interval of the ITS-M5 signal of 100 ms, as this change would just scale down the failure rate by a factor of 10.

The measured success rate is presented in Figures 21 through 24 as a function of the TX power in dBm.

Figure 21 shows the success rate of the HDR-DSRC system for a distance of 2,5 m.

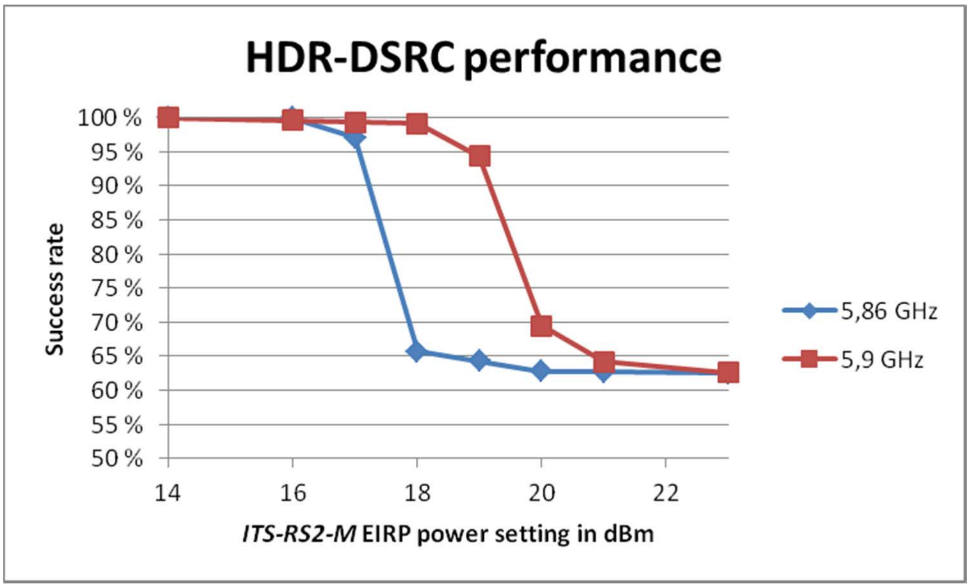

Figure 21: Success rate versus TX power in dBm at 2,5 m distance

Figure 22 shows the success rate of the HDR-DSRC system for a distance of 3 m.

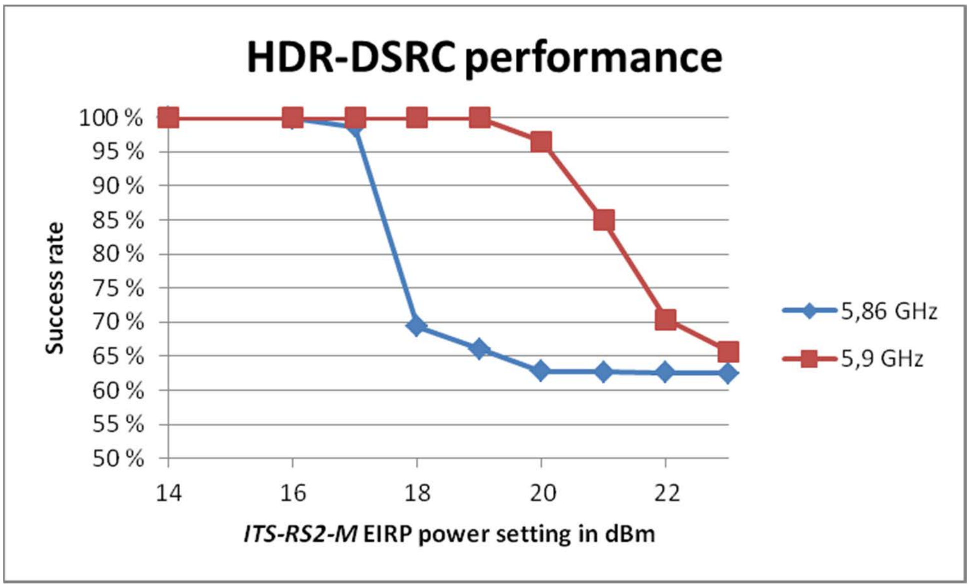

Figure 22: Success rate versus TX power in dBm at 3 m distance

Figure 23 shows the success rate of the HDR-DSRC system for a distance of 3,5 m.

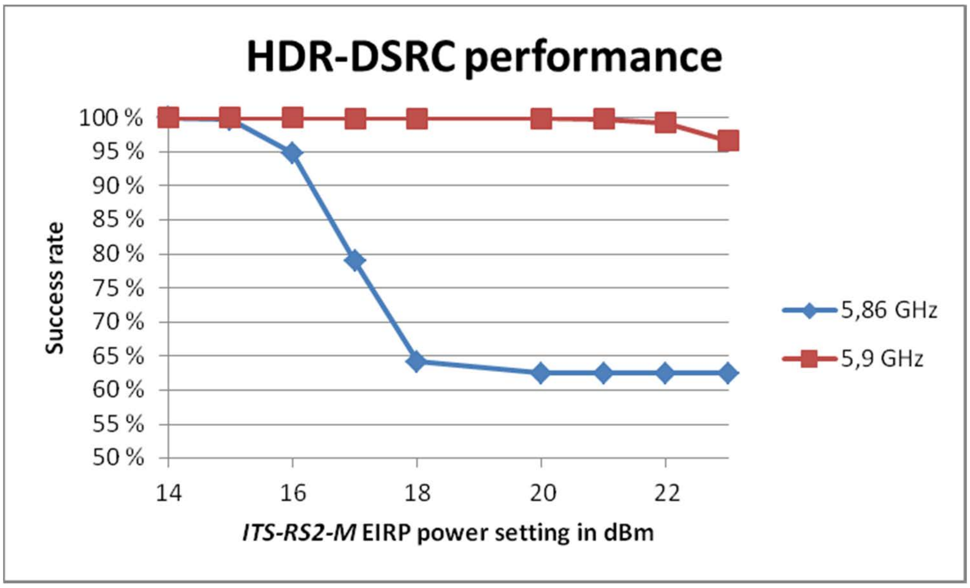

Figure 23: Success rate versus TX power in dBm at 3,5 m distance

Figure 24 shows the success rate of the HDR-DSRC system for a distance of 4 m. This series of measurements at 4 m distance is invalid, as a problem with the OBU battery was experienced; with no further spare batteries left.

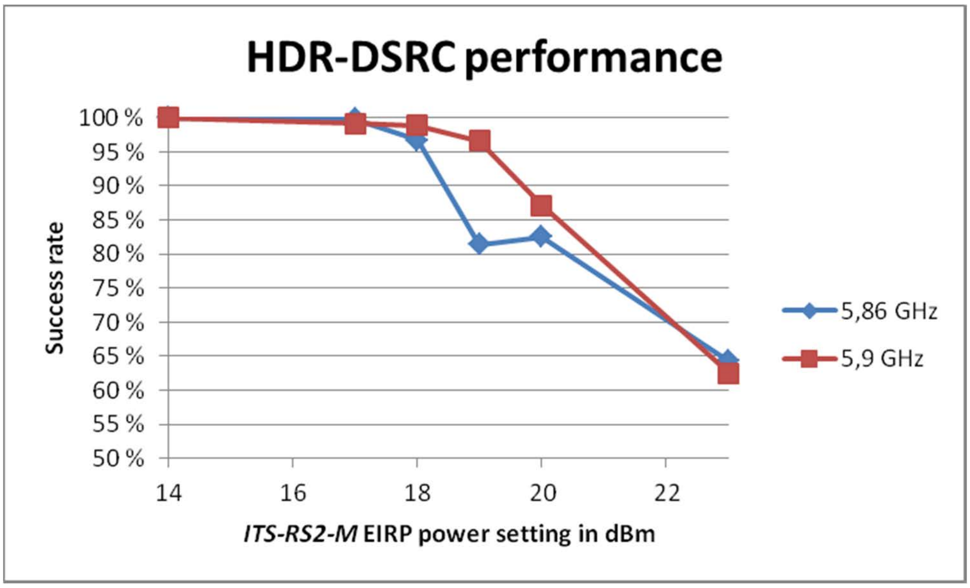

Figure 24: Success rate versus TX power in dBm at 4 m distance

5.3.3 Multiple interferers

5.3.3.1 Tests on toll plaza

Subsequently to the single interferer tests presented in clause 5.3.2.1, the situation with multiple interferers was investigated. Whilst the HDR-DSRC OBU still was installed inside the test vehicle as shown in Figure 6, the ITS roof-top antennas were installed on tripods at various short distances equivalent to the position of neighbouring cars on the same lane behind the test vehicle and at the side of the test vehicle, but never in front of the test vehicle.

Figure 25 illustrates five configurations how the test equipment was installed; the red box indicates the (x, y) position (see Figure 1), of the HDR-DSRC RSU, the blue box indicates the (x, y) position (see Figure 1) of the HDR-DSRC OBU, and the triplets of red circles indicate the positions of triplets of roof-top antennas.

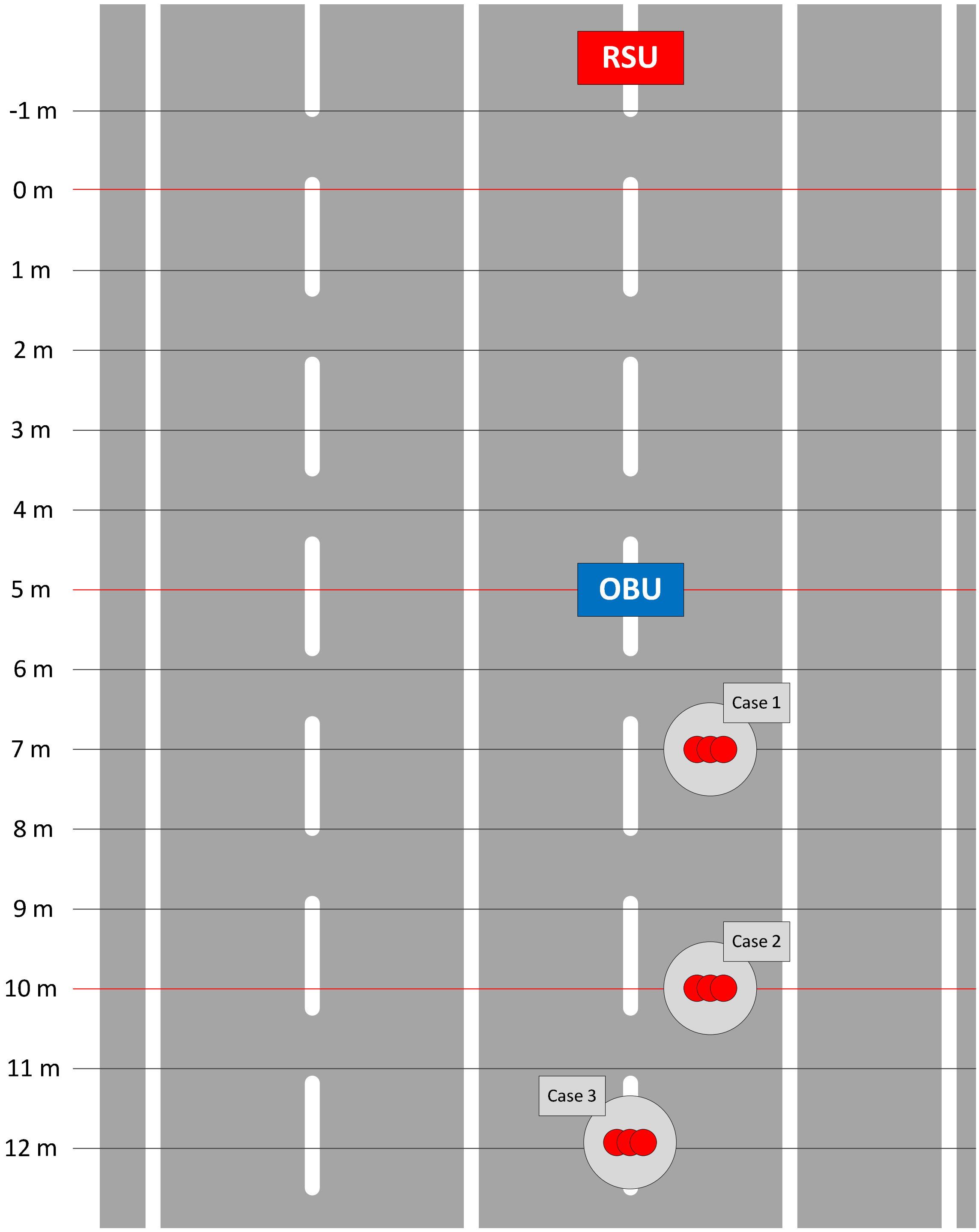

Figure 25: Test configuration with multiple interferers

With three ITS transmitters simultaneously operated at 5,86 GHz with maximum TX power, and the antennas installed virtually at the same location, the success rates presented in Table 7 could be measured as a function of distance of the HDR-DSRC OBU to the centre of the three antennas, measured in direction of the lane (see Figure 20).

Table 7: Success rates for multiple interferers

Case	Distance	Success rate
1	2 m	25
2	5 m	55
3	7 m	100

NOTE: The duration of three interfering ITS signal with 2 300 octets random data is about T_{d2} = 9,21 ms. Consequently three synchronized ITS transmitters each operating with the repetition rate of T_{p2} = 10 ms fill up the channel almost completely. According to the statistical model presented in Annex A, the probability for collisions and potential interference thus is 100 %.

5.3.3.2 Tests in anechoic chamber

Test set-up C is given by two ITS-SU roof-top antennas installed at the side of the HDR-DSRC OBU such that the two ITS-SU roof-top antennas are exactly in one line, perpendicular to the direction towards the HDR-DSRC RSU at the same *y* position (see Figure 20), as the HDR-DSRC OBU. This double-interferer test set-up is illustrated in Figure 26. The centre frequency of the ITS-SU transmitter was set to $f_{c,ITS}$ = 5 860 MHz. The positions x_{M5} and y_{M5} of the roof-top antennas were:

$$y_{M5} \leq y_{OBU}, various\ distances$$

$x_{M5} \approx 2\ m.$

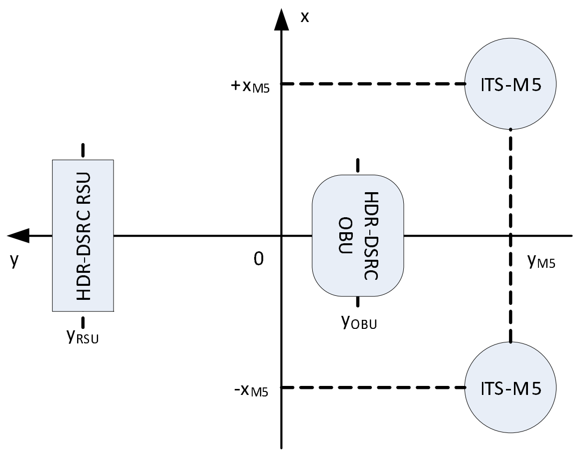

Figure 26: Test set-up C (distances in cm)

The various test runs used different values of the ITS-M5 positions y_{M5}. Harmful interference could be observed only for $y_{OBU} = y_{M5}$, i.e. the interfering stations being exactly at the side of the interfered HDR-DSRC OBU.

Figure 27 shows the HDR-DSRC performance for this case, with the distance of the ITS-M5 antennas to the HDRC-DSRC antenna set to x_{M5} = 2 m.

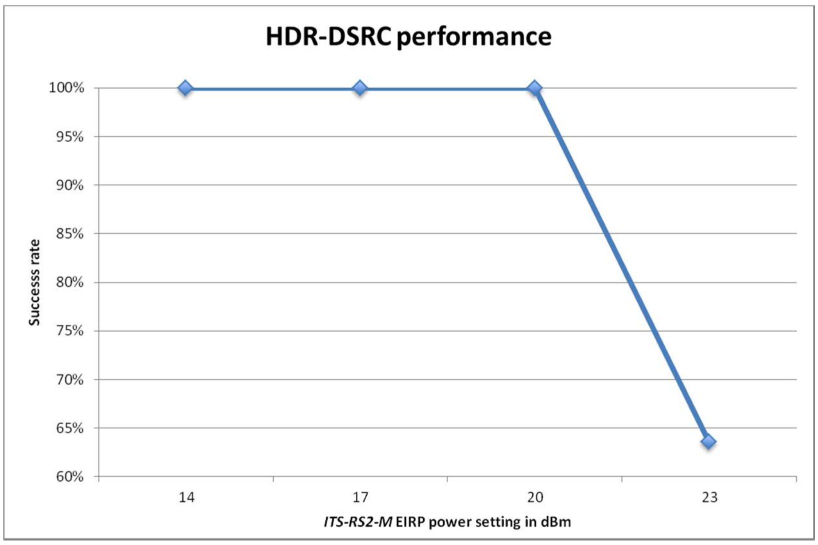

Figure 27: Test set-up C - HDR-DSRC performance for $y_{OBU} = y_{M5}$, and x_{M5} = 2 m

5.4 Summary of results

5.4.1 Critical scenarios

Based on the measurement results, the following critical scenarios were identified:

- radome on roof of vehicle, containing HDR-DSRC OBU and a single interferer (self-interference);
- single interferer in front of vehicle equipped with HDR-DSRC OBU (scenario for most harmful interference);
- vehicle with interferer overtaking another vehicle equipped with HDR-DSRC OBU.

More complex scenarios result from combinations of the above listed critical scenarios.

5.4.2 Coexistence scenarios

Based on the measurement results, the following limits to mitigate harmful interference were identified:

- the ITS-SUs upper TX power limit is 14 dBm EIRP;
- the lower distance limit between a HDR-DSRC OBU and an ITS-M5 interferer transmitting with 23 dBm EIRP is 5 m;
- the ITS-M5 repetition interval of 100 ms is not resulting in harmful interference.

5.4.3 Summary of performed tests and their results

See the Executive Summary.

6 Mitigation techniques

6.1 Techniques for CEN DSRC

Mitigation techniques for MDR-DSRC (CEN DSRC) are specified in [i.7].

6.2 Techniques for HDR-DSRC

The HDR-DSRC measurements indicate that the mitigation techniques specified in [i.7] for MDR-DSRC, i.e.:

- reduce TX power to 10 dBm EIRP;
- increase message repetition interval to 100 ms

are also applicable and sufficient to avoid harmful interference to HDR-DSRC.

NOTE: An optional implementation feature being part of potential mitigation techniques identified in [i.7] is the usage of a DSRC detector to identify presence in a DSRC tolling zone. There are chip sets supporting both MDR-DSRC and HDR-DSRC.

7 ETSI plug test

At the ETSI plug test in Livorno in November 2016, initial tests on the efficiency of proposed mitigation techniques to protect HDR-DSRC EFC communications were performed. Due to very limited time available for these tests, no statistical data could be gathered.

Major results of these tests are:

- applying mitigation techniques, EFC transactions were successfully performed;

- HDR-DSRC OBUs might wake-up outside of toll plazas by high-power ITS-M5 communications.

A first request to perform an ETSI plug test dedicated to HDR-DSRC issues was positively acknowledged by a representative of ETSI CTI. Whether and when such a plug test will be organized is not yet decided.

Potential tests to be considered for a further ETSI plug test may include conformity of ITS equipment with respect to mitigation techniques:

- Detection of toll plaza.
- Changing parameters in the ITS equipment in line with required mitigation techniques.

Annex A: Statistical prediction

In order to model the interference scenarios, the HDR-DSRC test signal is presented as a periodic signal with signal length T_{d1} and repetition period of T_{p1}. Similarly, the ITS signal is presented as a periodic signal with signal length T_{d2} and repetition period of T_{p2}. The time difference between the two signals T_r is random, an equal distribution of T_r in the interval:

$$0 \leq \mathrm{T_r} < \mathrm{T_{p1}} \tag{A.1}$$

is assumed with the restrictions:

$$\mathrm{T_{d1}} + \mathrm{T_{d2}} < \mathrm{T_{p1}} < \mathrm{T_{p2}}. \tag{A.2}$$

that do not affect generality.

This is illustrated in Figure A.1, with "Signal 1" being the HDR-DSRC test signal, and "Signal 2" being the ITS signal.

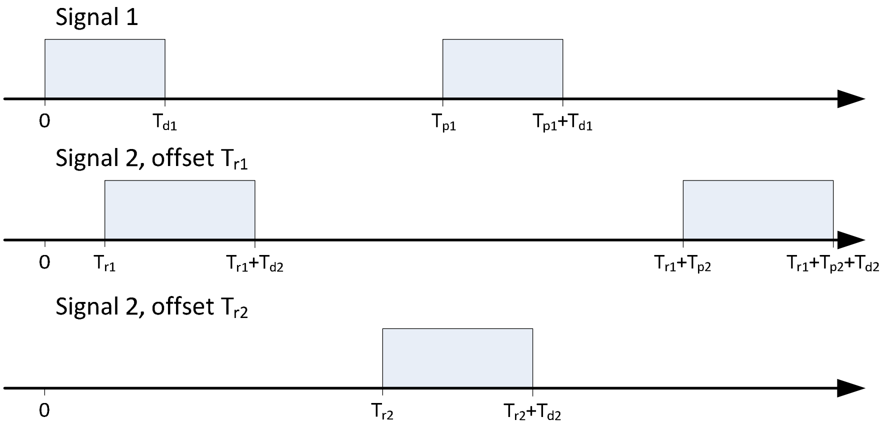

Figure A.1

Continuous overlap of signals, and thus continuous interference, occurs if:

$$T_{d1} + T_{d2} \geq min\left\{T_{p1}, T_{p2}\right\}. \tag{A.3}$$

Further on, interference based on partial overlap occurs for the two situations presented in Figure A.1 (Offset T_{r1} and T_{r2}) where equation A.3 does not apply. In this case, the likelihood for overlap is given by equation A.4:

$$\mathrm{P_{overlap}} = \frac{\mathrm{T_{d1}+T_{d2}}}{\mathrm{min}\left\{\mathrm{T_{p1}}\middle|\mathrm{T_{p2}}\right\}}. \tag{A.4}$$

It is assumed that, with severe interference, every partial overlap results in a potential loss of a HDR-DSRC message.

NOTE: In a real EFC environment even in the case of a message loss, retransmission mechanisms may ensure that a tolling transaction is effectively completed in an acceptable time. This latter case, however, is not taken into account in this simplified analysis.

For the timing situation, presented in Figure A.1, considering a severe interference situation, the probability of lost HDR-DSRC signals is:

$$P_{loss,1} = P_{overlap}, \tag{A.5}$$

and the probability of successfully transmitted HDR-DSRC signals thus is:

$$\mathrm{P_{success,1}} = 1 - \mathrm{P_{loss,1}}. \tag{A.6}$$

Now assume that with:

$$T_{p2} > T_{p1} \tag{A.7}$$

(The situation given in the tests that were performed) there can be N_{S1} packets of "Signal 1" within the time span T_{p2}, i.e. the repetition period of "Signal 2", with:

$$N_{S1} \approx \left\lfloor \frac{T_{p2}}{T_{p1}} \right\rfloor, \tag{A.8}$$

of which a single one is damaged with the probability presented in equation A.5; thus the overall "Signal 1" packet loss probability is:

$$P_{loss} = \frac{(N_{S1}-1)\cdot 0 + P_{loss,1}\cdot 1}{N_{S1}} = \frac{P_{loss,1}}{\left\lfloor \frac{T_{p2}}{T_{p1}} \right\rfloor} \approx \frac{T_{p1}\cdot P_{loss,1}}{T_{p2}}. \tag{A.9}$$

The overall HDR-DSRC performance success rate thus is:

$$P_{success} = 1 - P_{loss} = 1 - \frac{T_{p1}\cdot P_{loss,1}}{T_{p2}} = \frac{T_{p2} - T_{p1}\cdot P_{loss,1}}{T_{p2}}. \tag{A.10}$$

With $P_{loss,1}$ from equation A.5:

$$P_{success} = \frac{T_{p2} - T_{p1}\cdot \frac{\mathrm{T_{d1}+T_{d2}}}{\min\{\mathrm{T_{p1}}|\mathrm{T_{p2}}\}}}{T_{p2}} = \frac{T_{p2} - T_{p1}\cdot \frac{\mathrm{T_{d1}+T_{d2}}}{T_{p1}}}{T_{p2}} = 1 - \frac{\mathrm{T_{d1}+T_{d2}}}{T_{p2}}. \tag{A.11}$$

Numerical results related to the test configurations are presented in Table 3.

History

Document history		
V1.1.1	June 2017	Publication