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Rail to Digital automated up to autonomous train operation

D25.4 – FRMCS Isolation requirements for simultaneous operation of RMR and MNO services

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EXECUTIVE SUMMARY

This deliverable addresses a key technical challenge for the deployment of the Future Railway Mobile Communication System (FRMCS): how to ensure onboard coexistence between Railway Mobile Radio (RMR) services and public Mobile Network Operator (MNO) services when both are operated simultaneously on the same train. The topic is relevant because future railway communication architectures are expected to use hybrid connectivity, combining dedicated railway spectrum with public mobile network bearers to improve coverage, resilience, availability and/or capacity. However, the onboard environment creates a more demanding coexistence situation than general spectrum-sharing cases, because radio systems installed on the same vehicle may interfere with each other continuously while the train is moving through changing radio conditions. And as a mission critical communication system, the stability of the FRMCS connection is of high importance for train operation.

The objective of the work is to identify isolation requirements and practical implementation constraints for the parallel onboard operation of FRMCS RMR bands and selected public MNO frequency bands. The study focuses on the FR1 spectrum below 6 GHz and considers FRMCS band n100 in the 900 MHz range and FRMCS band n101 in the 1900 MHz range. The most relevant interference direction is from MNO uplink transmissions towards FRMCS reception, since public radio equipment and railway radio equipment may be installed on the same train. Attention is therefore given to the adjacent-band cases MNO n8 towards FRMCS n100 and MNO n1 towards FRMCS n101.

The technical approach combines several complementary elements. Coexistence calculations done outside of this study can be seen as an upper boundary. They are based on equipment specifications, conformance limits and worst-case assumptions such as maximum transmit power, full resource block allocation with the highest allowed out-of-band or spurious emissions and lowest received power at the FRMCS victim receiver.

Then the effect of modem architecture was analysed, in particular the role of internal duplexers in FDD radio modems. This leads to significant lower isolation requirements for the adjacent bands compared to the upper boundary calculation.

To complement the calculations and simulations, laboratory tests were performed using representative MNO user equipment and a prototype FRMCS modem. The tests recorded and analysed MNO interferer signals and then replayed them into an FRMCS connection while increasing the interferer power until a measurable throughput degradation occurred. The laboratory results showed significantly lower isolation needs than the specification-based calculations. The deliverable also highlights that measurements were conducted with a prototype FRMCS receiver and detailed isolation values might be device specific.

The difference between calculated and measured results can be attributed to several factors, including the performance of real equipment compared with specification limits, the use of internal

duplexers in FDD modem architectures and possible 5G interference-mitigation mechanisms in the FRMCS receiver.

With calculated values, simulation results and lab test results available, a proposal on isolation values to be further used within onboard deployment was elaborated considering the different sources as given in Table 1.

Band combinations	Calculation	Simulation	Measurement	Proposed isolation value	Notes on derivation of onboard isolation values
n20 --> n100 (blocking)	60		36	45	20/28 didn't show difference in the Labtest, n20 in Range 2, n28 in Range 3 (ETSI TS 138 101-1: Table 7.6.3-2), n8 UL is much closer to n100 with 51dB calc., 45 seems reasonable
n28 --> n100 (blocking)	45		36	45	value from calculation
n8 --> n100 (Blocking)	51		35	51	value from calculation
n8 --> n100 (OoB)	92	73	50	73	value from simulation, diplexer is needed for all full duplex modems, not device specific
n3/n7 --> n101 (blocking)	45		11,5	45	value from calculation
n78 --> n101 (blocking)	45			45	value from calculation
n1 --> n101 (Blocking)	64		36,5	64	value from calculation
n1 --> n101 (OoB)	89	73	48,5	73	value from simulation, diplexer is needed for all full duplex modems, not device specific

Table 1: Proposed isolation values and derivation

A concept study compares different implementation variants, the isolation requirements and the usage of different frequency bands to create a decision base. Taking the train specific implementation aspects into account, a distance of 2 m between the antennas was used for the study. Beside combined RMR and MNO capability within the same radio module, also separated RMR and MNO radio modules are analysed against installation complexity and feasibility. Starting with the calculated isolation values, as a next step, the proposed isolation values were considered in the concept study. It gives a comparative overview on different frequency bands, modem variants, deployment feasibility and complexity. Excluding the adjacent bands n1 and n8 would reduce the complexity of the onboard setup significantly as no filters at the MNO TX would be necessary.

A train-specific implementation analysis highlights that antenna placement and train roof conditions are decisive for achieving the required isolation in practice. Train onboard radio systems are constrained by available roof space, existing antennas, metallic structures, pantographs, roof equipment and vehicle-specific geometry. The distance and orientation between antennas, as well as the presence of obstacles, directly influence coupling and therefore the achievable isolation. Measurements on train roofs, including the Siemens Vectron example described in the report, provide valuable evidence that actual isolation can vary considerably with antenna position and vehicle layout.

The report also extends the analysis to migration from GSM-R to FRMCS, since parallel operation of legacy and future railway radio systems will need to be supported during the transition phase. For

this scenario also additional lab tests are recommended as the analysis is based on worst-case calculated values.

ABBREVIATIONS AND ACRONYMS

Abbreviation / Acronym	Meaning
3GPP	3rd Generation Partnership Project
5G NR	5th Generation New Radio
ATO	Automatic Train Operation
BAW	Bulk Acoustic Wave
DAC	Digital-to-Analog Converter
DL	Downlink
ECC	Electronic Communications Committee
eMBB	Enhanced Mobile Broadband
ETCS	European Train Control System
ETSI	European Telecommunications Standards Institute
FDD	Frequency Division Duplex
FR1	Frequency Range 1
FRMCS	Future Railway Mobile Communication System
FSL	Free-Space Loss
GSM-R	Global System for Mobile Communications – Railway
MNO	Mobile Network Operator
MOCN	Multi-Operator Core Network
OOB	Out-of-Band
RB	Resource Block
RF	Radio Frequency
RMR	Railway Mobile Radio
RX	Receiver / Reception
SCS	Subcarrier Spacing
SRS	System Requirements Specification

TDD	Time Division Duplex
TOBA	Train Onboard Architecture
TX	Transmitter / Transmission
UE	User Equipment
UL	Uplink

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1 INTRODUCTION

Coexistence between different mobile communication system is a challenging topic as the spectrum is getting more crowded from year to year. Regulation and standardisation procedures take care that different systems that might be run by different operators can coexist without interfering each other. Modern communication systems offer a broad set of interference mitigation technologies, find a summary in (1). Conformance measurements are defined to make sure that the equipment comply to the specifications. As a 5G based system, FRMCS makes use of the 3GPP and ETSI based compliance framework. However, the following railway specific frame conditions raise the necessity to take a deeper look at the topic when it comes to the operation of different mobile broadband systems in parallel on a train:

1. As a mission critical system FRMCS needs to fulfil a much higher level of availability as e.g. public networks. Connectivity losses have a direct impact on train operation.
2. Compared to public mobile networks, the spectrum available for Railway operation (band n100 and n101) is very limited. Interference mitigation technologies, that are based on changing the frequency band if the quality of a certain band is not sufficient, can work here only with limited bands available.
3. As both systems are installed on the same train, the interfering system is permanently present, while FRMCS reception level changes through the movement of the train

As those conditions are not considered in general coexistence studies and there is a high demand to use public frequencies in parallel to the RMR frequencies in future railway operation R2DATO Task 25.3 was studying the topic of FRMCS Isolation requirements for simultaneous operation of RMR and MNO services.

This deliverable begins with an overview of frequency bands and use cases for hybrid network technologies. Chapter 3 then describes the isolation requirements between RMR and MNO frequency bands. It explains the methodology and feasibility of calculations carried out by Ericsson in (2), simulations, analysing the effect of an internal duplexer included in full-duplex FDD modems, as well as lab tests conducted under Task 25.3, to compare calculated results with actual measurements. Finally, the chapter discusses the reasons for any differences observed and proposes suitable isolation requirements for a concept study on deployment feasibility.

The isolation requirements have a direct impact on train antenna deployment. Chapter 4 evaluates train specific implementation aspects and gives an example how isolation can be calculated. As the propagation condition can be impacted by the (often metallic) train roof and possible obstacles between the antennas, measurements between antennas on a train roof have been conducted.

Chapter 5 analyses different possible modem variants and provides a concept study for the proposed frequency bands and isolation values which provides a summary on the implementation

effort and feasibility. This is done with the calculated values and as an additional step including the results of the lab test.

Within the migration phase from GSM-R to FRMCS, parallel operation of FRMCS and GSM-R also needs to be supported and included into onboard concepts. Chapter 6 provides a first analysis on migration scenarios from GSM-R to FRMCS.

2 FREQUENCY BANDS AND HYBRID NETWORK TECHNOLOGIES

The relevant frequency range for this study is FR1 below 6 GHz. Figure 1 gives an overview on the bands used by public providers and the purple marked Railway Mobile Radio (RMR)-bands n100 and n101. n100 is today in use with GSM-R and will be used in Frequency Division Duplex (FDD) mode, Uplink and Downlink are separated in frequency. n101 is a Time Division Duplex TDD (TDD) band.

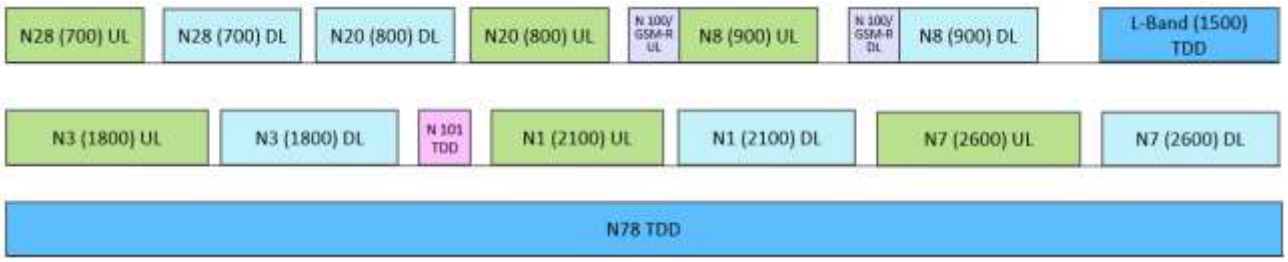


Figure 1: Relevant frequency bands for FRMCS coexistence.

FRMCS shall support the following RMR-frequency bands:

n100 FDD	n101 TDD
874.4-880.0 MHz UL 919.4-925.0 MHz DL	1900-1910 MHz

Table 2: FRMCS frequency bands

The regulatory framework for the harmonised use of the RMR frequency bands is defined in ECC Decision 20(02), see (3). The relevant specifications are defined by 3GPP in (4) and for FRMCS by ETSI-RT in (5).

For this study only interferences on the RMR band are considered as here a dedicated coverage can be assumed. The MNO bands can be divided into adjacent bands and bands in the spurious domain. For this study looking at the onboard coexistence, the UL signal of the interfering MNO band is relevant. The relevant adjacent bands to the FRMCS DL bands are:

Adjacent bands (UL –> DL)
N8 UL → N100 DL
N1 UL → N101 (TDD)

Table 3: Adjacent bands

Interference on MNO bands is not considered here. Due to the great amount of bandwidth available in the public networks, interference mitigation can be done by switching frequency bands and/or resource blocks. The usage of public frequencies is only considered here as part of the FRMCS system (e.g. as fallback), no external systems (e.g. for passenger-connectivity) using mobile broadband are considered.

2.1 USE CASES AND ARCHITECTURES FOR HYBRID FRMCS NETWORKS

Public frequency bands are discussed to be used for different use-cases. The following hybrid network use cases are included in FRMCS SRS Chapter 12 (Bearer flexibility) in (6).

1. Application specific Data Path selection
2. Fallback
3. Coverage extension
4. Resilience through best path selection
5. Resilience through packet replication
6. Capacity extension

The possible Use Cases and network architectures are described in detail in in the Signal & Draht article: 5G-RACOM – field study on hybrid FRMCS networks for resilient rail communications, see (7).
In hybrid FRMCS network architectures, future railway applications that primarily use private FRMCS networks will be able to leverage the additional and independent infrastructure from public 5G networks and access an additional frequency spectrum. This is advantageous for increasing resilience and availability in railway communications by means of the parallel use of multiple independent connections (i.e. data paths). It can also provide capacity enhancement for bandwidth-intensive services, offloads non-critical traffic when necessary and improve overall coverage (7).

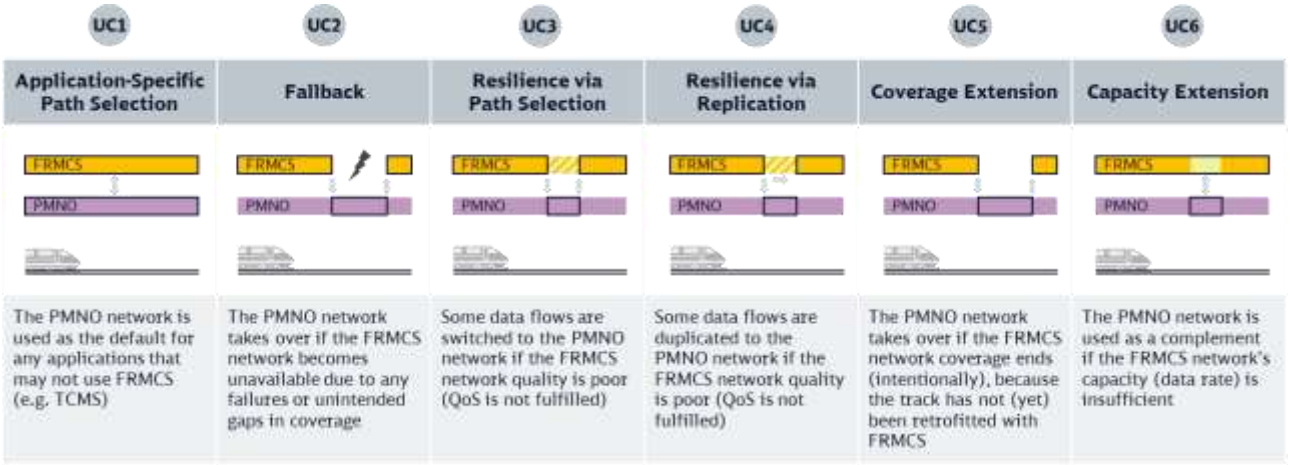


Figure 2: Hybrid network use-cases from (7)

There are multiple hybrid FRMCS network architecture options available to support the use cases, see Figure 3. Each architecture provides certain characteristics and is subject to availability and applicability in the specific country or organisation, while taking factors such as legislation, coverage, the technologies in use and the business and operating models into account (7). The results of the 5G-RACOM multipath fieldtests has been published in (8).

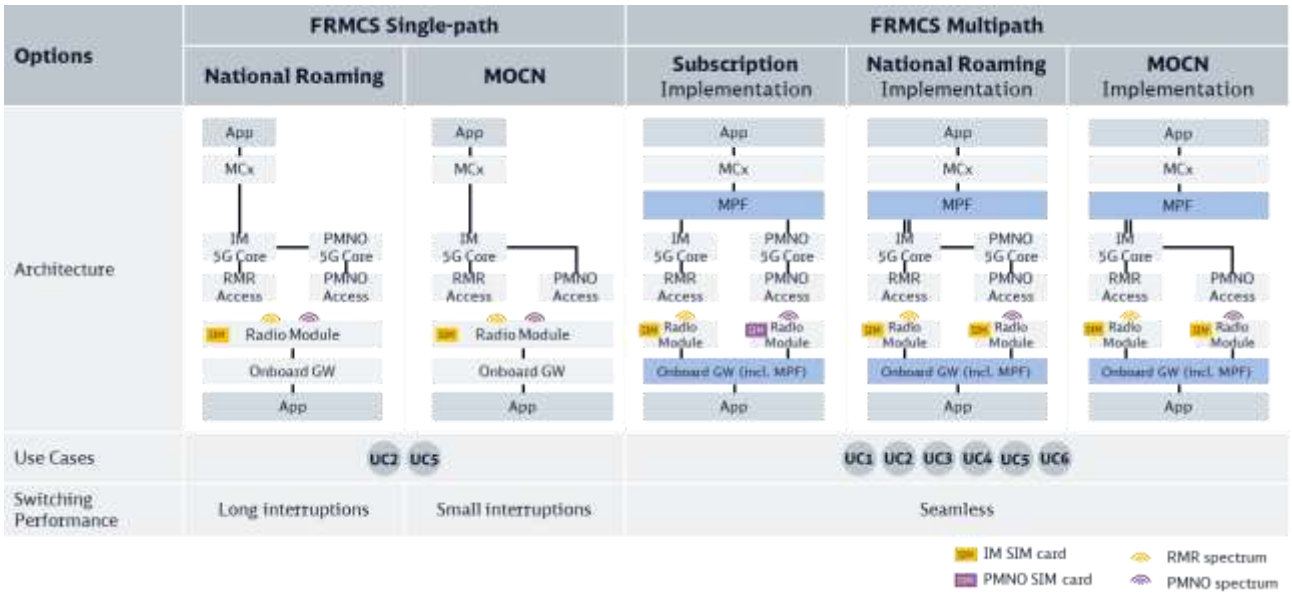


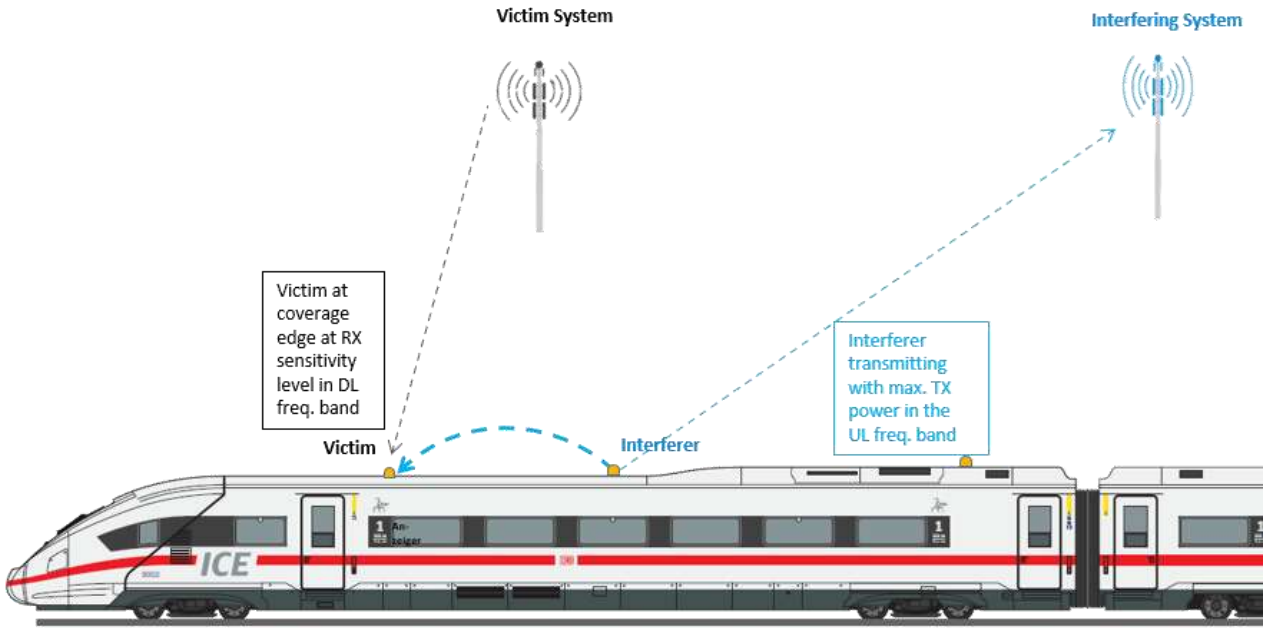
Figure 3: Hybrid network architecture variants from (7)

The Onboard support of public frequency bands is included in FRMCS SRS Chapter 8 (Spectrum) as MV-3 topic (6) and shall be further studied. As there are different possibilities for the onboard

architecture. FRMCS Modems will possibly support both, RMR and MNO frequencies. But variants with RMR band Modems only and separate MNO modems might also be feasible. For FRMCS multipath at least two modems are required.

3 ONBOARD ISOLATION REQUIREMENTS

To achieve high availability for mission critical services, relevant interferences on the physical layer between the different RMR systems and potential public MNO systems running in parallel on the train must be avoided. Worst case scenario: interferer is located on the same train as the victim system, thus, in worst case, with constant uplink transmission, resulting in a permanent interferer for the victim system.



The most relevant disturbance mechanisms are blocking and out-of-band emissions for nearby adjacent bands. Spurious emissions and intermodulation are additional disturbance mechanisms.

3.1 COEXISTENCE CALCULATION

The calculation on RMR – MNO Coexistence has been performed by Ericsson in (2). Basis are the UE characteristics specifications (4) and (5), defining the limits a device needs to fulfil in worst case (e.g. high temperature, full TX power) for conformance testing.

For the calculation several worst-case scenarios are assumed:

- Full TX power of the interfering signal
- Full RB usage of the interfering signal
- Lowest RX power level of the victim system

The details of the calculation are available in (2). In Table 4 and Table 5 the results of the calculation of the isolation requirements of the neighbouring MNO bands towards n100 and n101 are given.

Calculated isolation requirements for FRMCS 900 (n100)			
	MNO Band 8 UL: 880-912 DL: 925-960	**MNO Band 20** UL: 832-862 DL: 791-821	**MNO Band 28** UL: 703-748 DL: 758-803
Isolation due to blocking (dB)	51	60	45
Isolation due to unwanted emissions (dB)	92	61	61
Isolation required (dB)	92	61	61

Table 4: Calculated isolation requirements for FRMCS 900 (n100)

Calculated isolation requirements for FRMCS 1900 (n101)					
	MNO n1 UL: 1920-1980 DL: 2110-2170	**MNO n3** UL: 1710-1785 DL: 1805-1880	**MNO n7** UL: 2500-2570 DL: 2620-2690	**MNO n38** 2570-2620 TDD	**MNO n78** 3300-3800
Isolation due to blocking (dB)	64	45	45	45	45
Isolation due to unwanted emissions (dB)	89	61	61	61	61
Isolation required (dB)	89	61	61	61	61

Table 5: Calculated isolation requirements for FRMCS 1900 (n101)

For FRMCS900 (n100) as a victim the highest required isolation is 92 dB to protect Radio modem operating in frequency band n100 from unwanted emission of MNO band 8.

For FRMCS1900 (n101) as a victim the highest required isolation is 89 dB to protect Radio modem operating in frequency band n101 from unwanted emission of MNO band 1.

3.2 DUPLEXER IN FDD SYSTEMS

The operating mode of a Radio modem in frequency band n8 and n1 is Frequency Division Duplex (FDD). There are two types of FDD: Half duplex and Full duplex. The Half duplex mode is used for low-cost radio device for IOT where no simultaneous Uplink and Downlink is necessary. In the NR User Equipment specification (4) which is the basis for the isolation calculation in section 3.1 the spectrum mask for the Half duplex FDD is given.

For operation in FDD full duplex, the unwanted emission cannot perturbate the receiver. This cannot be achieved without an internal duplexer. This will be demonstrated in this chapter.

The next figure shows a simplified architecture of a 5G-NR radio modem.

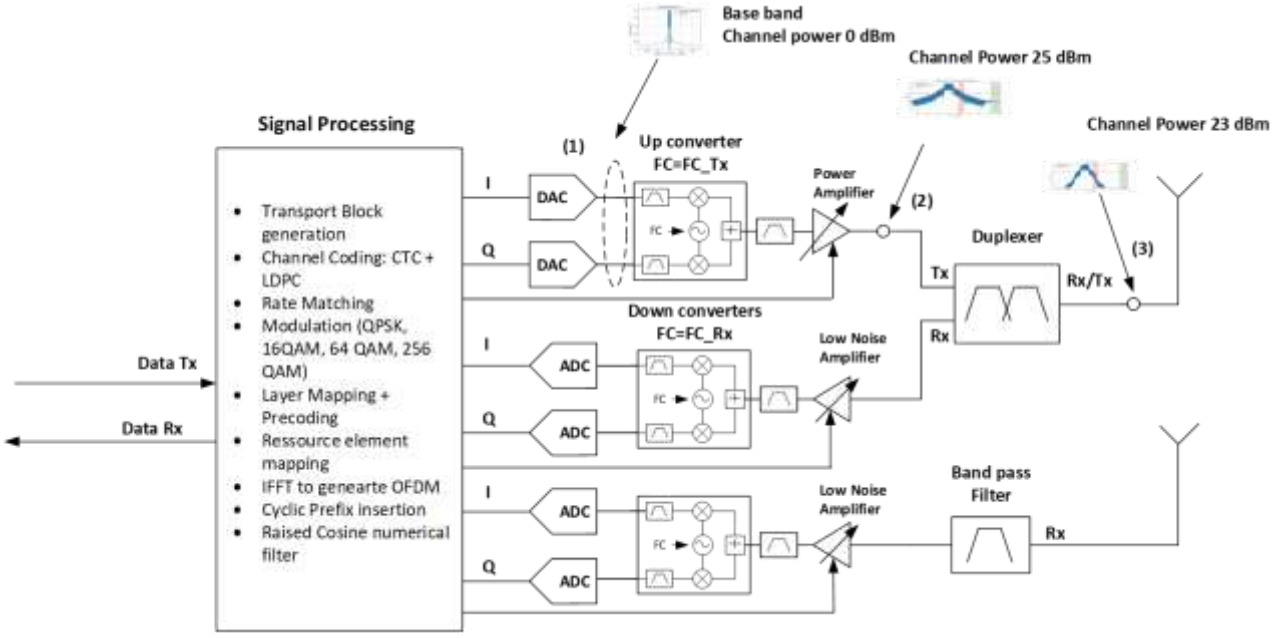


Figure 4: Simplified 5G-NR modem architecture

The transmission chain of the radio modem has been simulated. The parameters of the simulation are as follows:

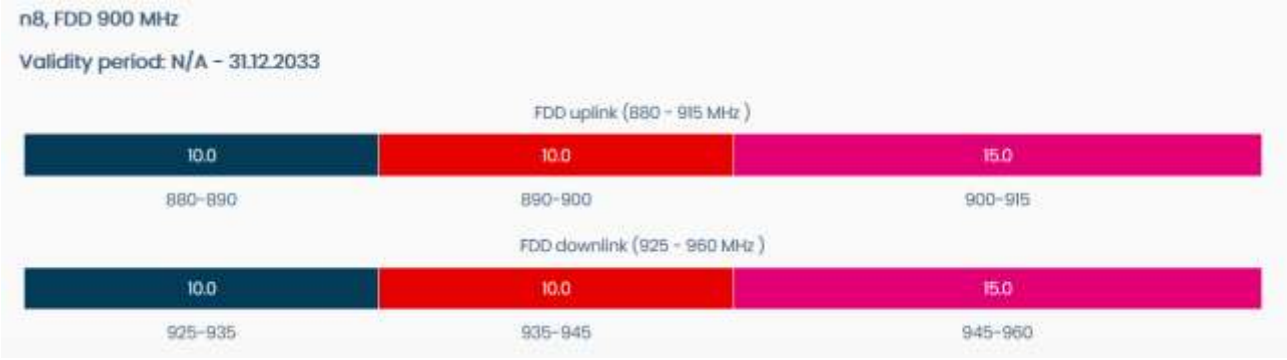
- RF signal simulated: 5G NR n8 with 910 MHz as centre frequency for Tx channel
- Assigned channel bandwidth 10 MHz
- Sub Carrier Spacing (SCS): 15 kHz
- Transmit power: 23 dBm at RF antenna connector
- Number of RBs: 52
- Allocation of RB: All the RBs are considered as allocated
- Occupied bandwidth: SCS*12*NRB = 9,360 MHz
- Power amplifier non linearities based on the RAPP model
- Oscillator Phase noise model: Leeson's
- Simulated Duplexer based on Quorvo Bulk Acoustic wave QPQ1270 BAW: 40–53dB @ 700–960 MHz: typical duplexer used inside 4G and 5G Nr radio modem
- Channel Power of the 5GNR n8 Tx channel after the power amplifier and before and after the duplexer
- Interference level computed in the 5G NR n8 Rx channel with 955 MHz as centre frequency after the power amplifier and before the duplexer
- Interference level computed in the FRMCS Rx channel 919.4 MHz – 925 MHz after the power amplifier and before the duplexer
- Interference level computed in the 5G NR n8 Rx channel with 955 MHz as centre frequency after the duplexer
- Interference level computed in the FRMCS Rx channel 919.4 MHz – 925 MHz before the duplexer
- Sample frequency: 24.576 MHz
- FFT size: 262144
- Frequency span: 787 MHz to 1033 MHz

The channel with 910 MHz as centre has been considered after analysis how the 5GNR n8 frequency band is allocated by different European Radio regulators.

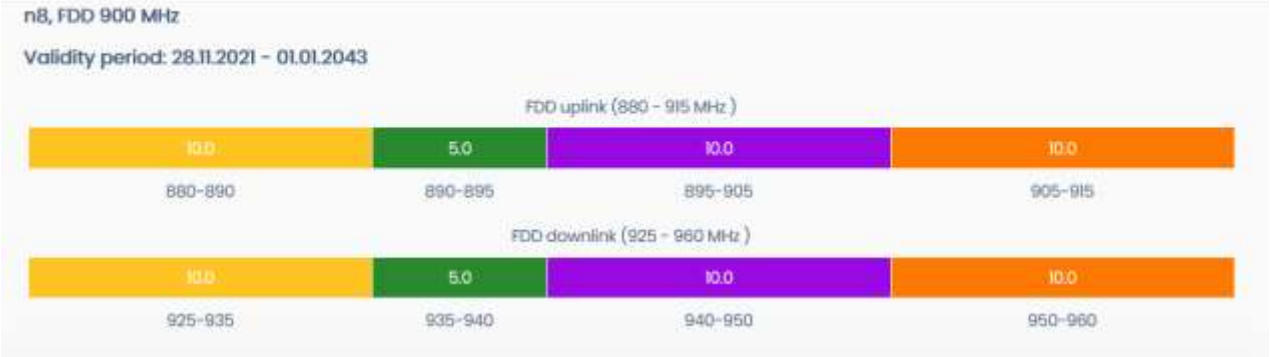
France frequency Allocation



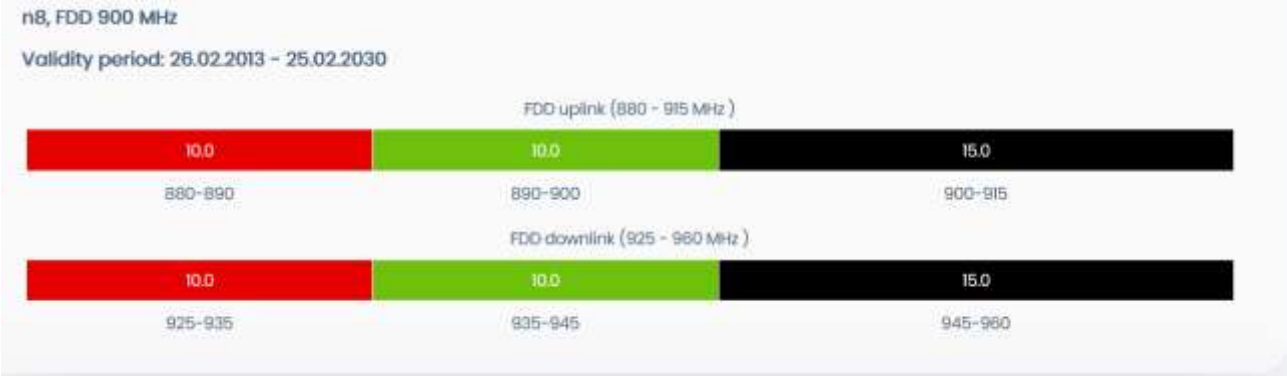
Germany frequency Allocation



Belgium frequency Allocation



Nederland frequency allocation



Source: https://www.spectrum-tracker.com/

The selected channel with a centre frequency of 910 MHz with and a channel bandwidth of 10 MHz is the one close to the limit of the Tx frequency 5G-NR n8 tx frequency band. The duplex frequency spacing is 45 MHz it means that the 5G-NR n8 DL-channel will have 955 MHz as centre frequency.

Figure 5 shows the base band spectrum at the output of the Digital Analog Converter (DAC) at interface (1) marked in Figure 4.

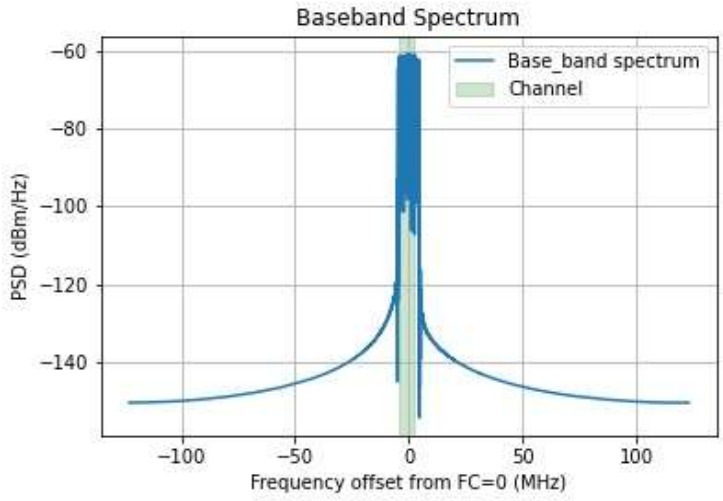


Figure 5: Base band spectrum at the output of the DAC.

The next figure shows the spectrum after the power amplifier and before the duplexer at interface (2).

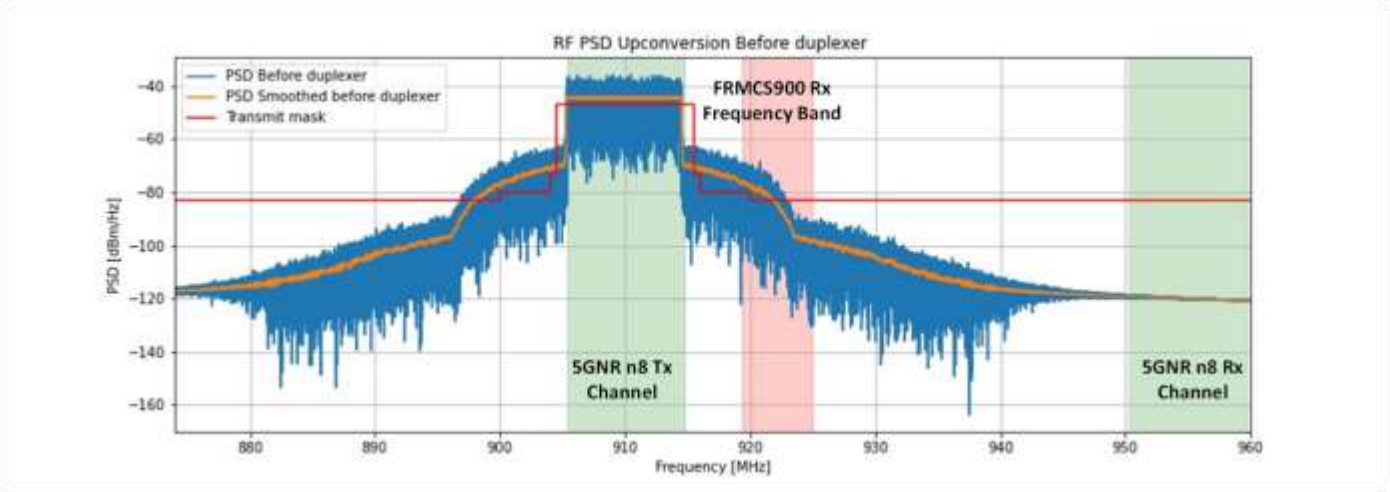


Figure 6: Spectrum after the power amplifier and before the duplexer

The the 5G-NR n8 channel bandwidth Tx and Rx are highlighted in green and the FRMCS 900 Rx band is highlighted in pink.

The x axis is frequency in MHz and y axis is power spectral density in dBm/Hz.

The total power in the Tx channel is 25 dBm/10MHz, 2 dB above the duplexer insertion loss.

The 5GNR interference level in the 5GNR Rx channel is - 50 dBm/10 MHz. This interference level is too high to allow full duplex transmission. The reference sensitivity is - 94 dBm/10 MHz, this means that the interference level is 44 dB above the reference sensitivity.

The interference level in the FRMCS 900 Rx band is - 13.7 dBm/5 MHz, close to the value obtained considering the spectrum mask specified in the Table 6.5.2.2-1 in (4). This value is 12 dBm.

The next figure shows the spectrum after the duplexer at RF interface (3).

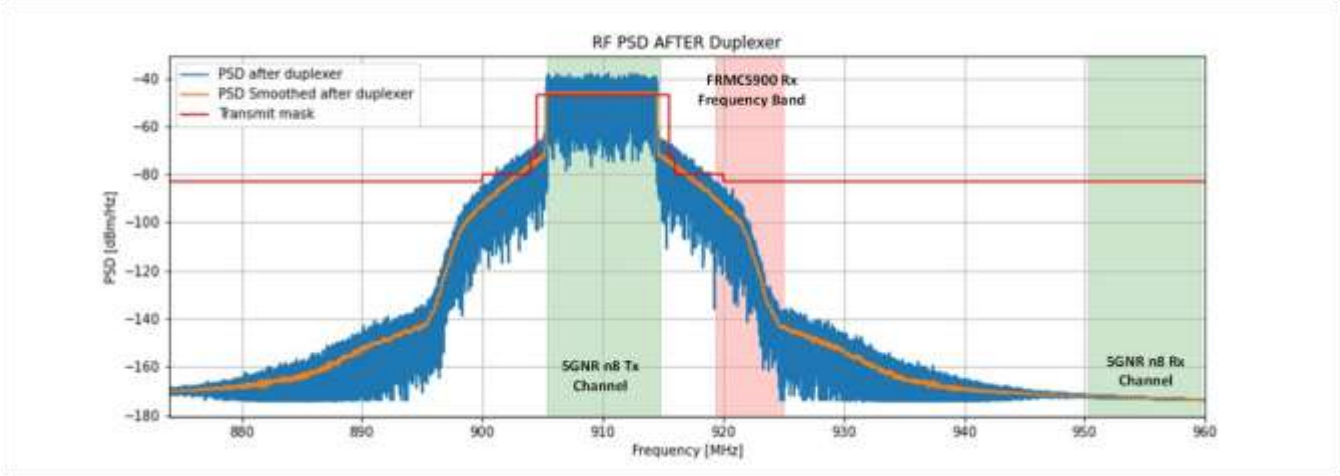


Figure 7: Spectrum after the duplexer.

The power in the 5G-NR n8 channel is 23 dBm/10 MHz. The interference level in the 5G-NR Rx channel is - 103 dBm/10 MHz corresponding to - 172 dBm/Hz, 2 dB above the noise floor and 9 dB below reference sensitivity. This interference level allows simultaneous transmission without mutual interference between Tx and Rx. FDD full duplex is possible.

The interference level in the FRMCS Rx frequency band is - 31 dBm/5 MHz, it means 17 dB lower than before the duplexer. This is a significant reduction.

The next table compares the required isolation between 5G-NR n8 and FRMCS900 to allow simultaneous operation of a 5G NR Radio modem designed for Half duplex FDD and a 5G NR radio modem designed for FDD full duplexer.

	Radio Modem FDD half Duplex-	Radio Modem FDD Full Duplex
	MNO Band 8 UL: 880-912 DL: 925-960	**MNO Band 8** UL: 880-912 DL: 925-960
Ptx (dBm)	23	23
Ptx _Unwanted (dBm)	**-12**	**-31,27**
Receiver Blocking level (dBm)	-26	-26
BW_rx (MHz)	5	5
NF_rx (dB)	5	5
KT dBm⁄Hz	-173,90	-173,90
10log10(KTB) (dB)	-106,91	-106,91
Noise Floor (dBm)	-101,91	-101,91
Receiver Desensitization Standard (dB)	3,00	3,00
Maximum Desensitization of the receiver (dB)	2,00	2,00
I/N (dB)	-2,33	-2,33
Maximum Interference Level (dBm)	-104,24	-104,24
Blocking (dBm)	-28,31	-28,31
Isolation due to blocking (dB)	51,31	51,31
Isolation due to unwanted emissions (dB)	92,24	72,97
Isolation required (dB)	92,24	72,97

Table 6: Comparison of isolation values for Half-Duplex and Full-Duplex FDD modems

The isolation required for a Radio modem designed for FDD full duplex with an internal duplexer is 73 dB compared to 92 dB.

It is reasonable to assume that Radio modems designed to be fitted in a router have been developed for Enhanced Mobile Broadband (eMBB) and optimized for FDD full duplex. These radio modems are expected to incorporate an internal duplexer based on bulk surface wave technology to achieve the required Tx/Rx isolation for FDD full-duplex operation.

Several manufacturers such as Qorvo and Broadcom have developed duplexers in surface mount packaging for the 4G and 5G NR market.

A similar analysis has been done for the 5G-NR n1 and FRMCS 1900. The simulation has been performed considering a 5G-NR n1 channel with 1930 MHz as Tx frequency and a channel bandwidth of 20 MHz. The Sub Carrier Spacing considered is 15 KHz. The number of RBs is 106.

The duplex spacing in the 5G-NR n1 frequency band is 190 MHz it means the Rx channel has 2120 MHz as centre frequency.

The simulated duplexer is based on the Quorvo Bulk acoustic wave QPQ1282.

The results of the simulation are as follows.

- Before the duplexer:
  - 5G-NR n1 Tx channel power 25 dBm/20MHz
  - Interference level in 5G-NR n1 frequency band: - 50 dBm/20 MHz
  - Interference level in the FRMCS 1900 Rx band: - 14.6 dBm/10 MHz
- After the duplexer:
  - 5GNR n1 Tx channel power 23 dBm/20MHz
  - Interference level in 5GNR n1 frequency band: - 99 dBm/20 MHz
  - Interference level in the FRMCS 1900 Rx band: - 28 dBm/10 MHz

The required isolation considering an interference level of -28 dBm is 73 dB instead of 89 dB.

3.3 LAB TESTS

To compare the calculated values, taking in to account several worst-case scenarios with the behaviour of real equipment, a lab test was planned. The labtest has been subcontracted to the company Funkwerk, that is developing the first FRMCS Modems, that are also planned to be used in the MORANE 2 project to verify FRMCS v2 specifications. The tested FRMCS modem (MTC18) was a stage 1 development prototype with known limitations regarding blocking behaviour and adjacent-channel power leakage. According to Funkwerk, the known stage-1 limitations do not affect the tested receive paths and interference frequency ranges. The blocking limitation concerns the n1 downlink range, while the tests considered n1 uplink interference, and the adjacent-channel power leakage limitation is not relevant to the FRMCS receive measurements. The full test report is available at (9).

The labtest was planned in two steps: First step was to record and analyse the signals from several public interferers as shown in Table 7.

#	Device	Operating System	IMEI	Build	Model
1	NOKIA X20	Android 13	355819290080252 355819295080257	00WW_3_510	TA-1341
2	ZEBRA TC27	Android 13	354053750166895 354605330167030	13-12-08.00-TG-U00-STD-ATH-04	WCMTB
3	Sony Xperia Z5[1]	Android 6.0.1	354187070205593	32.2.A.5.11	E6653
4	OnePlus 8	OxygenOS 13.1	865116046155139 865116046155121	IN2013_13.110.587 (EX01)	IN2013
5	FGW3	Linux			RM500

Table 7: MNO devices used for interference analysis

Second step was to playback the MNO band signals and couple them into a FRMCS connection. Then the power of the interferer was raised until an impact on the FRMCS throughput could be measured.

The results are specific to the tested prototype and laboratory setup.

3.3.1 Recording and analysis of the MNO signals

Figure 8 shows the setup for the recording of the public interferer signals with the Vector Signal Generator SMW-200-A. With the 5G Base Station simulator CMX 500 and the iperf network bandwidth measurement tool, traffic was generated over certain 5G configurations (max. Ressource Block allocation vs. limited RB allocation). The setup was chosen to produce reproducible results. Usage of public networks would not allow this as there is limited control over the traffic and used 5G configurations. As generally the 5G scheduler has implemented certain interference mitigation technologies (see (1)) the setup here can be seen as a worst-case scenario.

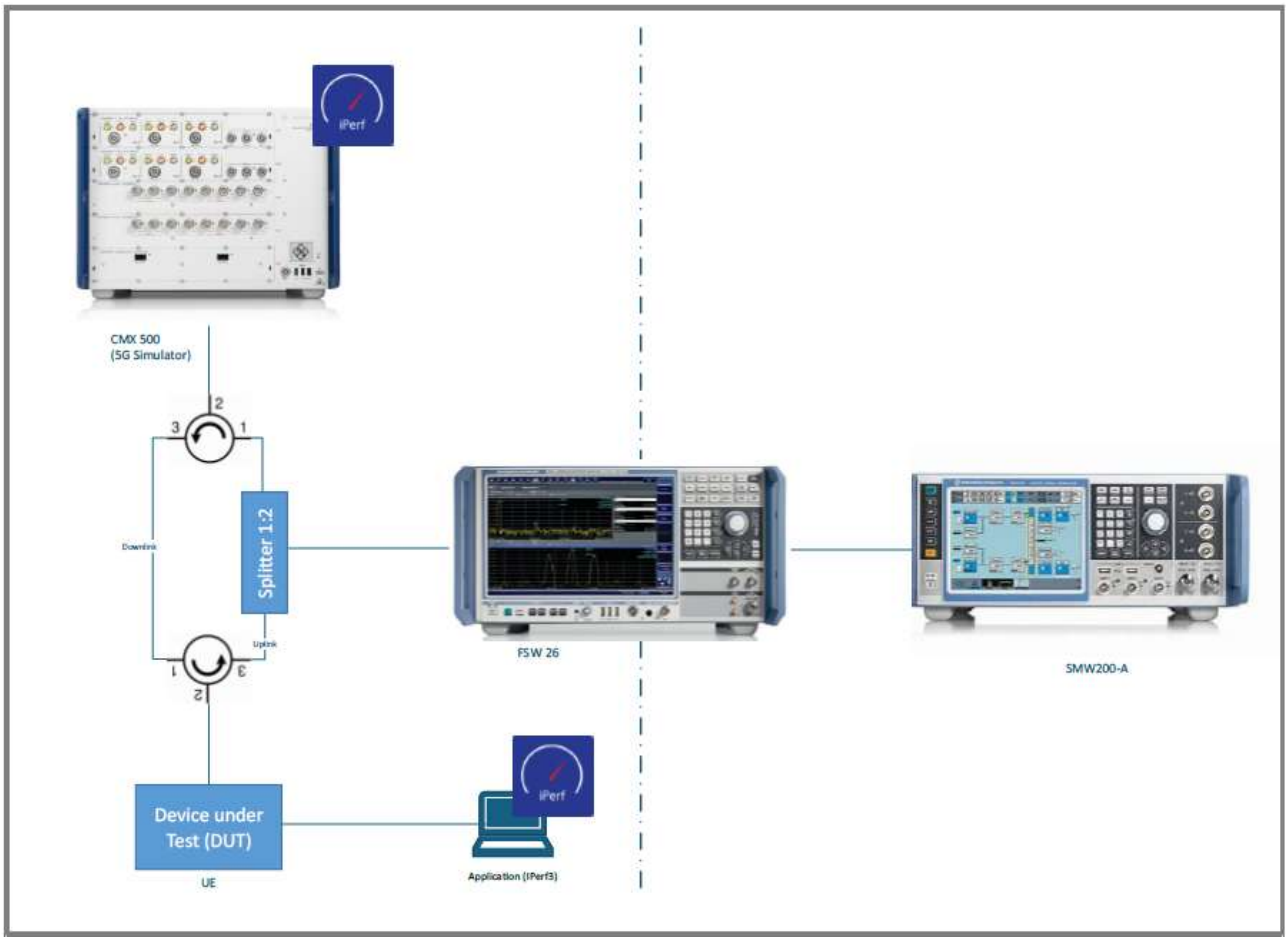


Figure 8: Setup for recording of the public interferers

Details on the measurement setup, equipment and used configuration can be found in (9). The analysis of the MNO signals has been done within the following frequency ranges:

Measurement Range 1: FRMCS n100 UL (874,4-880 MHz)

Measurement Range 2: FRMCS n100 DL (919,4-925 MHz)

Measurement Range 3: FRMCS n101 (TDD: 1900-1910 MHz)

The most relevant ranges for the onboard analysis are Range 2 and 3 as this is the range the FRMCS UE receiving the DL signals. Interferences falling into this range have an impact on the DL throughput.

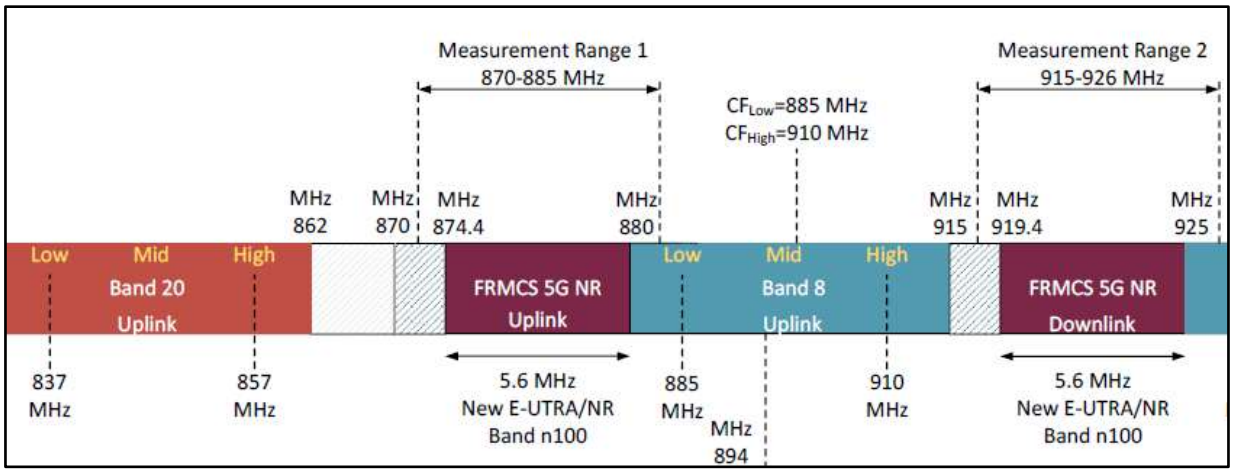


Figure 9: Frequency allocation of n100 and n8 Uplink

Figure 9 show the frequency allocation of FRMCS n100 and n8 and n20 Uplink. Two band allocations are defined within the public bands (High and Low). The High one was used for the worst-case analysis in Step 2 as it provides a higher interference level.

Figure 10 shows the spectrum of an n8 interferer with reduced RB configuration, Figure 11 for the maximum RB allocation. The difference in the Out-of-Band emissions can be clearly seen. For the reduced RB it is much lower.

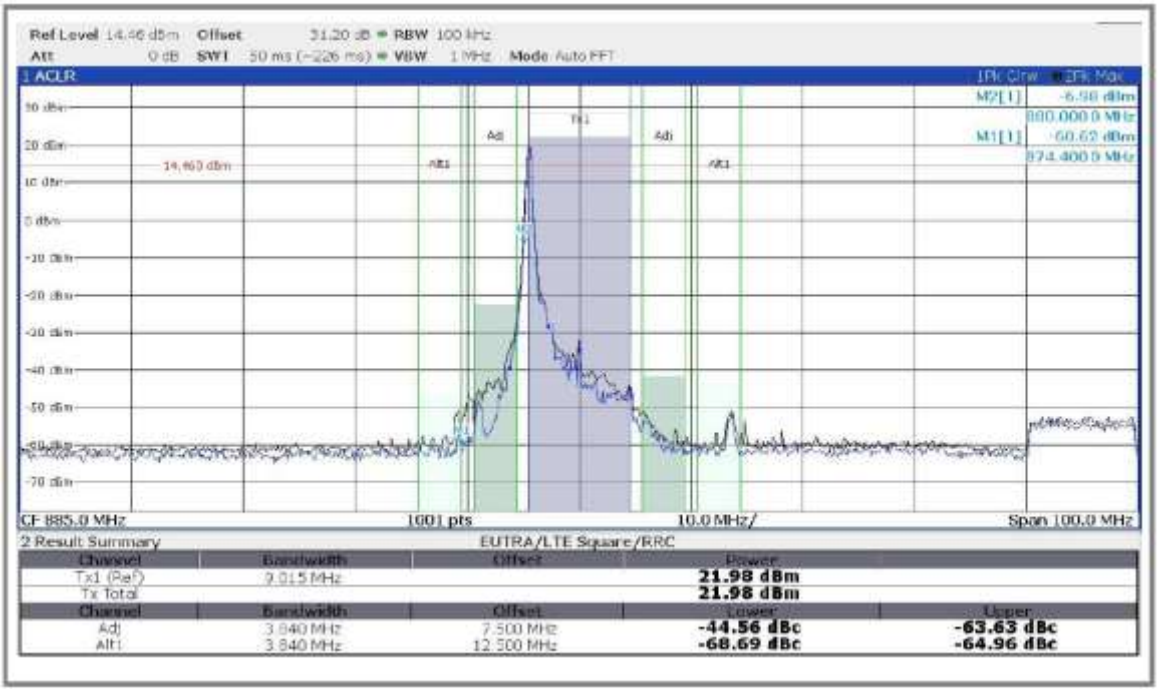


Figure 10: Public interferer (FGW-3) with reduced RB configuration and maximum power

For Step 2 the worst case of full RB allocation of the high band part was used.

The MNO bands with more distance to the RMR band (spurious domain) don't show significant signals falling into the RMR bands. See for example n28 on n100 in Figure 14. Also, combinations of frequency bands as used in carrier aggregation do not add significant signal levels to the RMR bands. Measurements from n78 on n101 and n100 didn't show any interfering spurious emissions in the relevant bands.

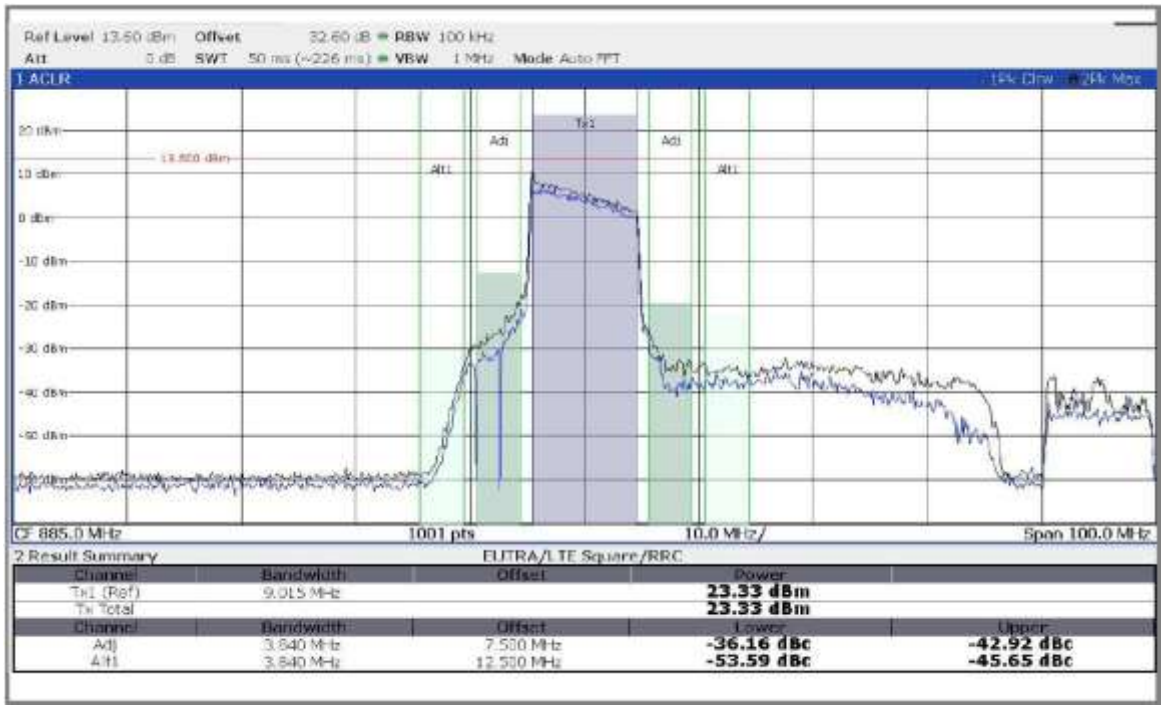


Figure 11: Public interferer (FGW-3) with maximum RB configuration and maximum power

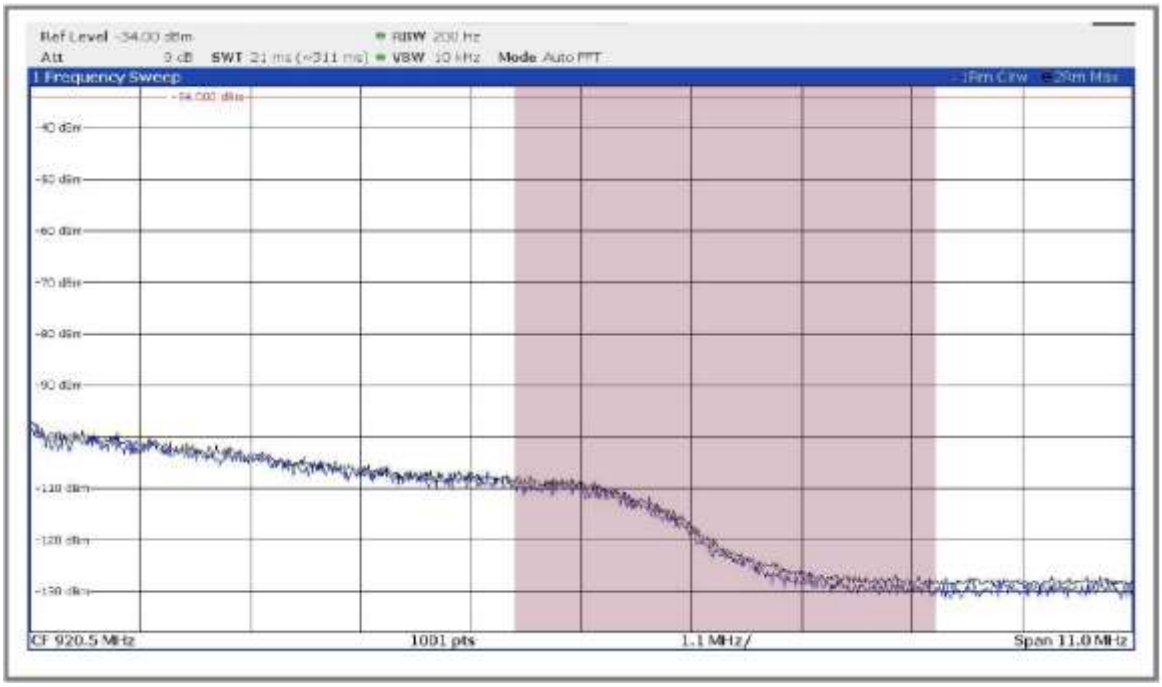


Figure 12: 25: OOB and Spurious Emissions in 919.4 - 925 MHz (FRMCS marked, full RB public, high band part)

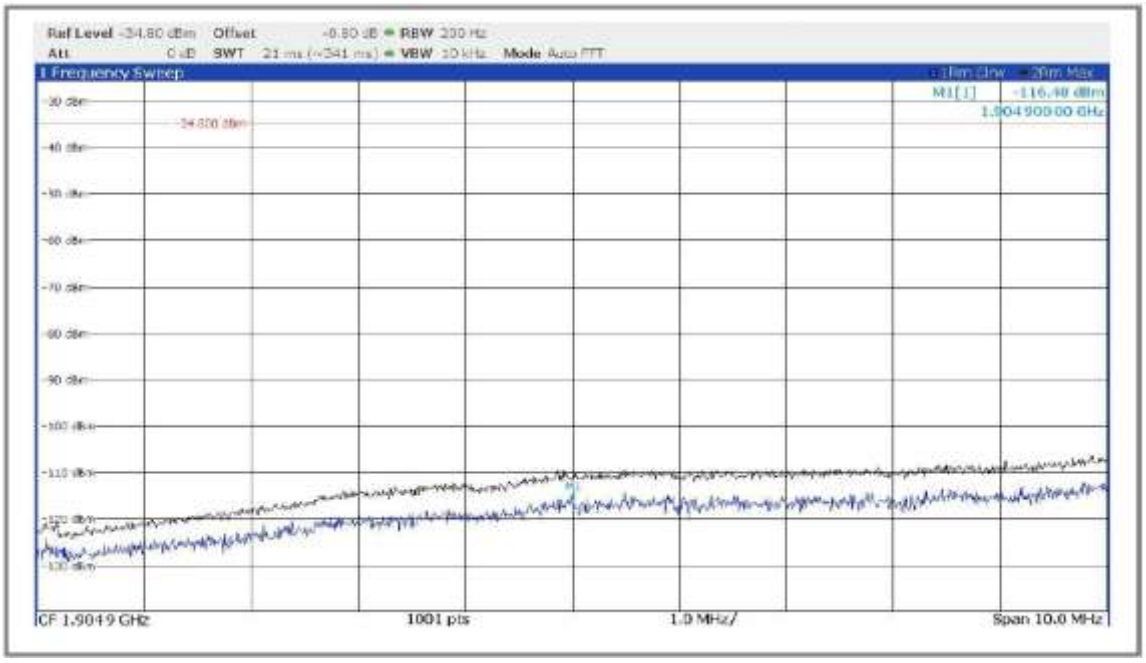


Figure 13: Impact of n1 PMNO towards n101

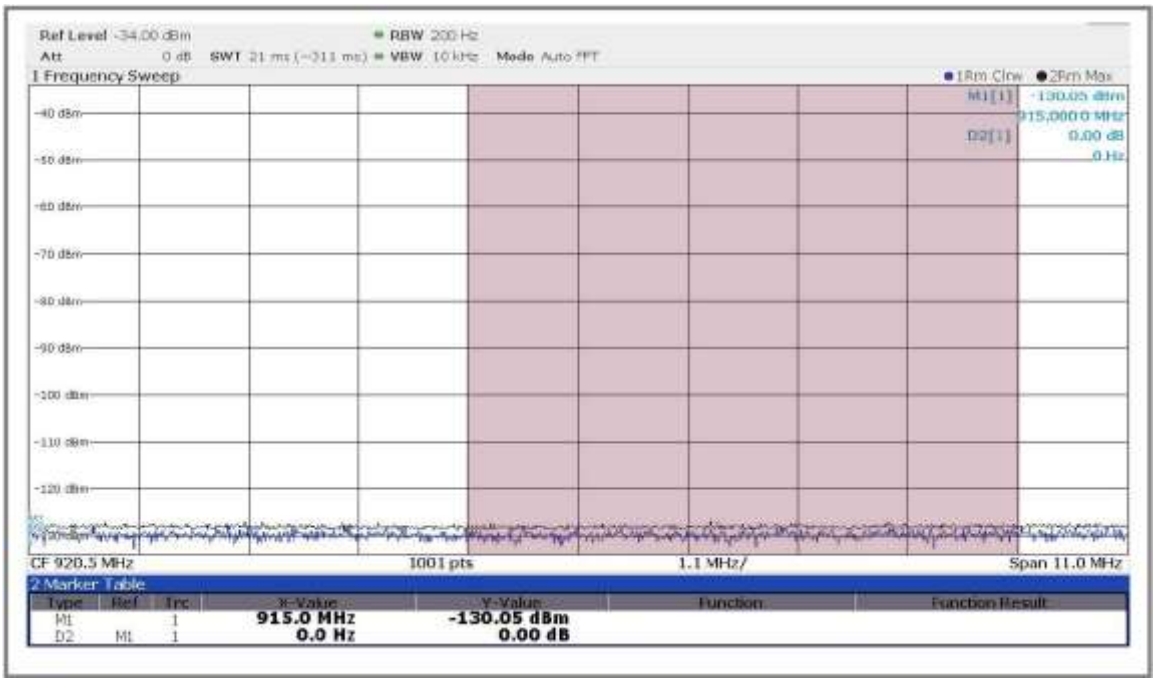


Figure 14: Out of Band and spurious emissions from n28 in 919.4 - 925 MHz (FRMCS marked, full RB public)

3.3.2 Measurements on the FRMCS side

Figure 15 shows the Lab setup for the interference measurements on the FRMCS side.

A 5G connection has been established between the CMX500 5G generator and the FRMCS UE. The power level was chosen to be close to the sensitivity level (-121 dBm) at the Downlink. Then iperf was started and the recorded interfering signal was coupled into the FRMCS path, and the power level was raised until a decrease in datarate in the FRMCS connection could be measured. The measurement was done with and without band reject filters as seen in Figure 16 for the FRMCS bands inserted to the TX path of the interfering signal. Without the filter included the interference of the Out-of-Band emissions are expected to be the dominant mechanism, with the filter the blocking effects are expected to become more relevant. The measurements were conducted with two different MNO UEs (one embedded, one integrated in a smartphone) that showed only small differences (~1,5dB). For the worst-case analysis, the lower value was taken, as this leads to higher isolation requirements.

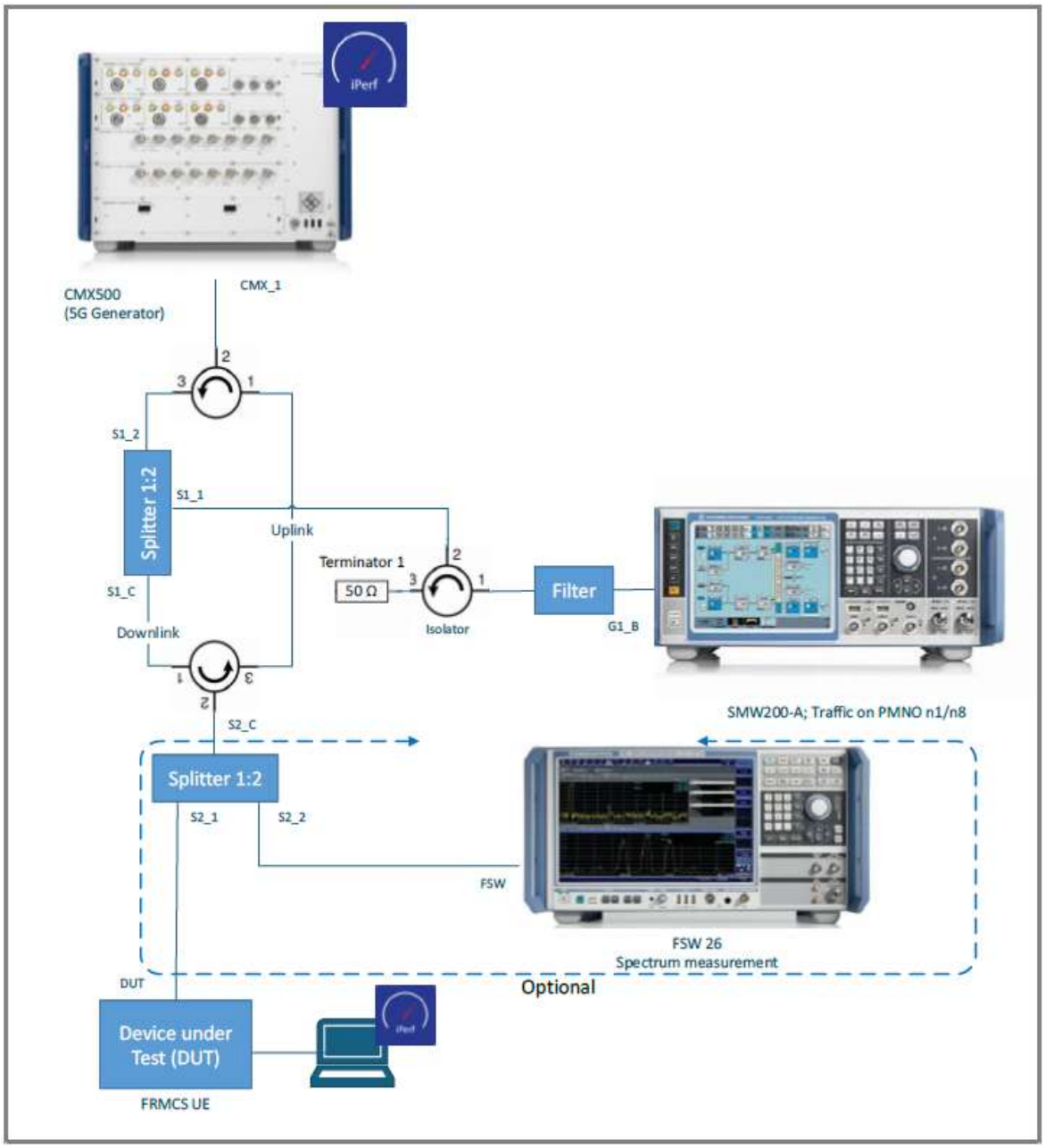


Figure 15: Setup for FRMCS measurements and replay of the recorded interferer

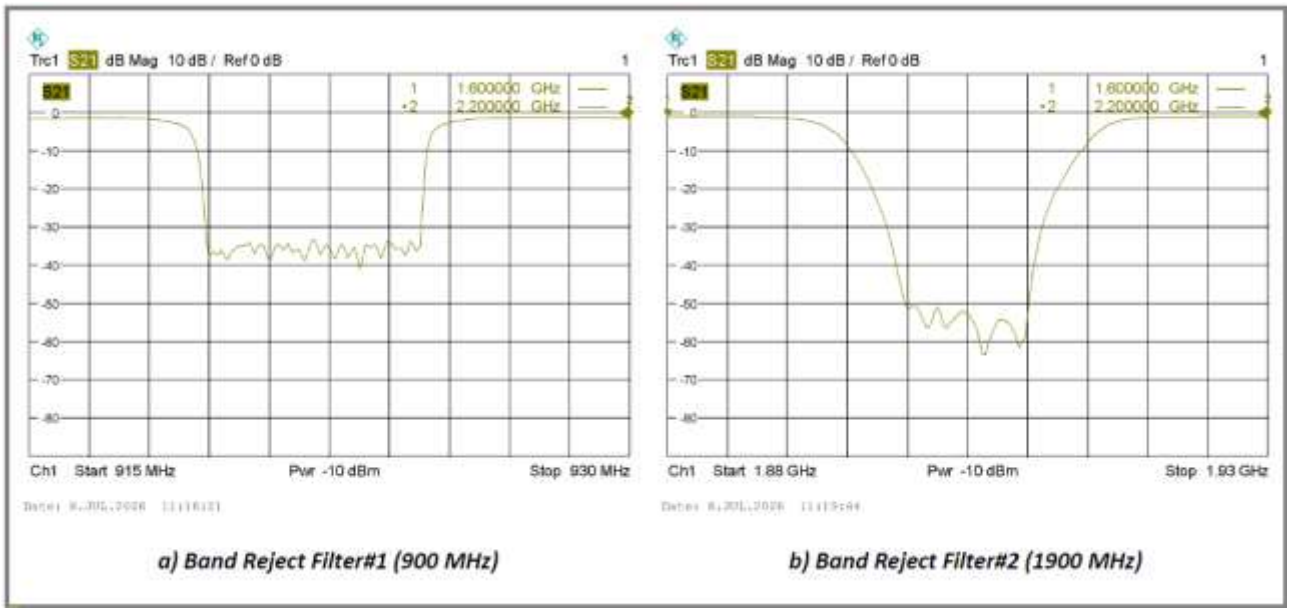


Figure 16: Band reject filters included in the TX path for blocking analysis

N8 → n100

Figure 17 shows the spectrum of the n100-n8 setup with filter#1 and n8 reference signal @ position 910 MHz. The signals shown here are:

M1: n100 UL

M2: n8 UL interferer

M3: n100 DL at -121 dBm

Table: 8 show the interference levels from band 8 towards n100.

The other frequency bands where measures in a similar way. The results are given in Table 10 and Table 11, also including the calculation of the isolation values and a comparison with the calculated values from the specifications as described in section 3.1.

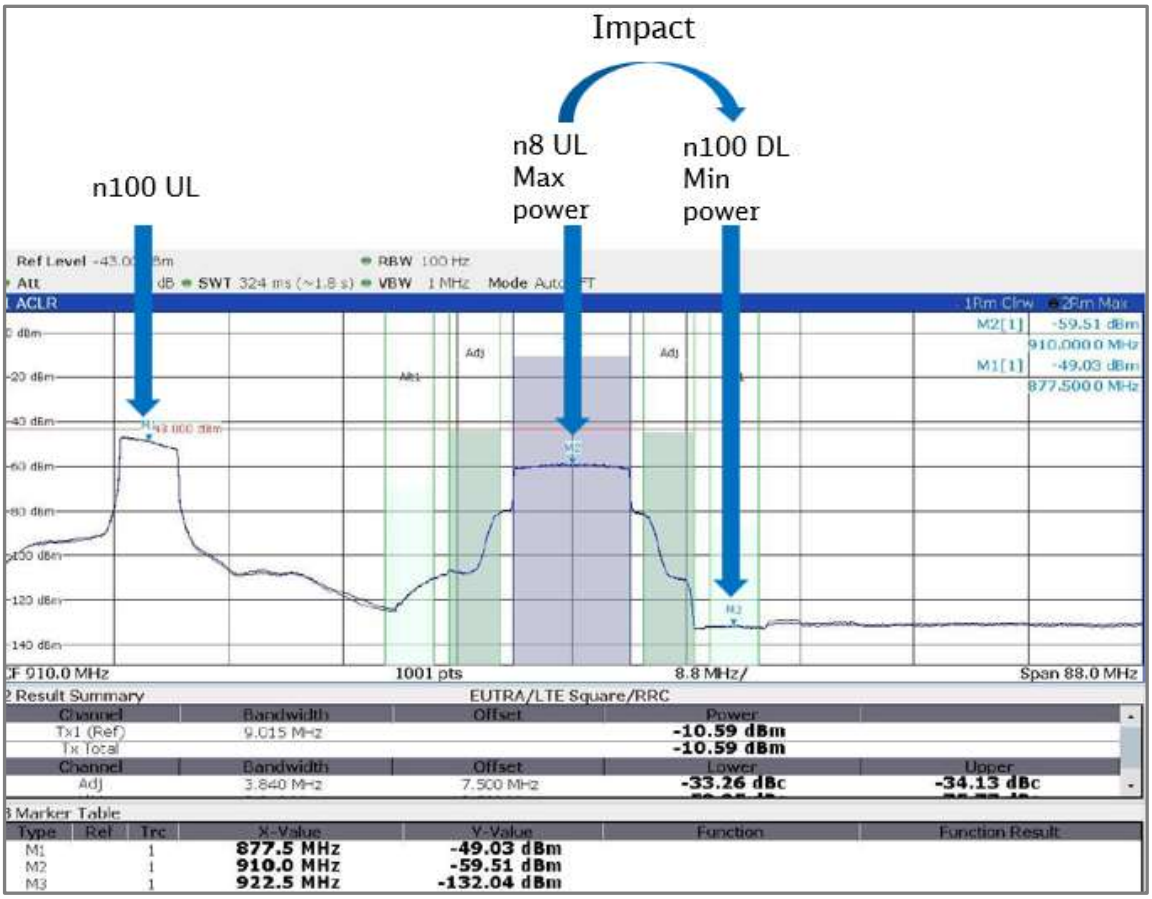


Figure 17: Blocking situation n100-n8 with filter#1 and n8 reference signal @ position 910 MHz

	Public-UE @ CF 885 MHz						Public-UE @ CF 910 MHz					
	Without Filter#1			Filter#1 active			Without Filter#1			Filter#1 active		
n8 level [dBm]	-23	-22,5	-22	-10	-5,5	-5	-30	-26	-25,5	-11	-10,5	-10
TX throughput [kbit/s]	1210	903	203	800	806	1000	1440	1400	739	1070	1360	372
Re-transmissions TX	0	1	0	0	0	1	0	0	0	0	1	0
RX throughput [kbit/s]	1220	756	355	1390	1230	623	1260	1310	706	1180	790	458
Re-transmissions RX	25	41	66	15	23	8	23	21	48	51	50	56
RSRP	-121	-121	-121	-121	-121	-121	-121	-121	-121	-121	-121	-121

Table: 8: Interference levels from n8 towards RMR in n100

3.3.3 Isolation calculation from the lab results

From the lab measurements the minimum isolation was calculated. The setup for the calculation is described in Figure 18.

The attenuation between the SMW 200-A and the FSW 26 and between the SMW 200-A and the MTC-18 was measured. As it is the same value for n100 it adds up to 0 dB difference. For n101 there is a 0,5 dB difference which needs to be considered in the calculation. Reference for the calculation it the input to the MTC-18. Here in worst case the 23 dBm power level of an interferer could be inserted if isolation would be 0 dB. The isolation necessary to prevent the interferer influencing the FRMCS connection then can be calculated back as included in Table 9 for n8 → n100 and n1 → n101 as examples.

Table 10 and Table 11 show results for the other frequency bands, also including a comparison with the calculated values from the specifications as described in section 3.1.

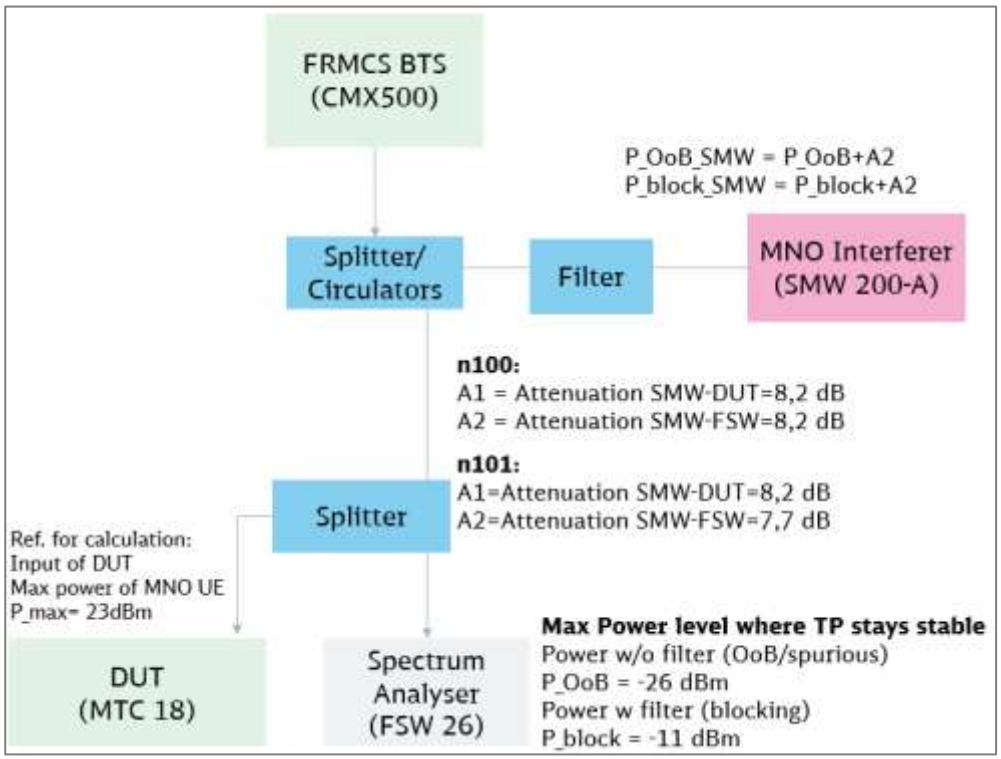


Figure 18: Setup for the isolation calculation.

Without filter: Focus on Out-of-band/spurious emissions	With filter: Focus on blocking effects
Isolation calculation n8 → n100	
I_OoB= P_max – P_OoB_SMW - A1 = P_max – P_OoB + A2 –A1 = 23dBm - (-26dBm) = 49 dB (+1dB for lab uncertainties)	I_block= Pmax – P_block_SMW –A1 = P_max – P_block + A2 –A1 = 23dBm – (-11dBm) = 34 dB (+1dB for lab uncertainties)
Isolation calculation n1 → n101	
I_OoB= P_max – P_OoB_SMW - A1 = P_max – P_OoB + A2 –A1 = 23dBm - (-25dBm) + 7,7 dB – 8,2 dB = 47,5 dB (+1dB for lab uncertainties)	I_block= Pmax – P_block_SMW –A1 = P_max – P_block + A2 –A1 = 23dBm – (-13dBm) + A2 –A1 = 35,5 dB (+1dB for lab uncertainties)

Table 9: Calculation of the isolation for n8--> n100 and n1 --> n101

	MNO Band 8 UL: 880-912 DL: 925-960		MNO Band 20 UL: 832-862 DL: 791-821		MNO Band 28 UL: 703-748 DL: 758-803	
	Calculation	Lab test result	Calculation	Lab test result	Calculation	Lab test result
Ptx (dBm) max.	23	23	23	23	23	23
Lab: Attenuation difference (SMW - DUT (dB))-SMW-FSW)		0		0		0
Lab results: Prx (min. Power of the Interferer at the DUT w/o filter/OoB) (dBm)		-26				
Lab results: Prx (min. Power of the Interferer at the DUT with filter/blocking) (dBm)		-11		-12		-11,5
Uncertainty factor from lab setup (ISO/IEC 17025) (dB):		1		1		1
Isolation due to blocking/Lab results with filter (dB)	51,3	35	60,1	36	45,1	35,5
Isolation due to unwanted emissions (dB)/Lab results w/o filter	92,2	50	61,2		61,2	

Table 10: MNO → n100 Lab test results and isolation calculation in comparison with the calculated values from the specifications

	MNO n1 UL: 1920-1980 DL: 2110-2170		MNO n3 UL: 1710-1785 DL: 1805-1880		MNO n7 UL: 2500-2570 DL: 2620-2690		MNO n78 3300-3800
	Calculation	Lab test result	Calculation	Lab test result	Calculation	Lab test result	Calculation
Ptx (dBm)	23	23	23	23	23	23	23
Lab: Attenuation difference (SMW - DUT (dB))-SMW-FSW)		-0,5		-0,5		-0,5	
Lab results: Prx (min. Power of the Interferer at the DUT w/o filter/OoB) (dBm)		-25					
Lab results: Prx (min. Power of the Interferer at the DUT with filter/blocking) (dBm)		-13		12		12	
Uncertainty factor from lab setup (ISO/IEC 17025) (dB):		1		1		1	
Isolation due to blocking/Lab results with filter (dB)	64,3	36,5	45,1	11,5	45,1	11,5	45,1
Isolation due to unwanted emissions (dB)/Lab results w/o filter	88,7	48,5	61,2		61,2		61,2

Table 11 : MNO --> n101 Lab test results and isolation calculation in comparison with the calculated values from the specifications

Comparing the calculated values from the specification with the lab results a quite high difference can be seen.

On the one hand side the modem architecture might play a role here. As explained in section 3.2 especially in FDD systems running in Full duplex an internal Duplexer needs to be integrated. With this the unwanted emission level of FDD bands n1 and n8 falling into the FRMCS bands n101 and n100 is reduced by approx. 20 dB.

For the spurious domain the TX analysis already showed a very low level of interfering signals outperforming the limits given in the specifications.

On the FRMCS reception side the internal 5G interference mitigation technologies as described in (1) might play a role here.

3.4 Discussion on Isolation Requirements for FRMCS operation

The question, whether sharing studies shall be based on typical device performance levels or limits defined within the specifications is not new. ECC report 249 (10) analyses the questions:

1. Should sharing/compatibility studies be based on typical performance of unwanted emissions rather than the limits?

2. Should those limits/levels in bands, adjacent to the operating one (and boundary between the OoB and spurious domains) be redefined or be re-considered on a case-by-case basis to better reflect actual performance of equipment, and therefore allow for increased opportunities for sharing/compatibility and more efficient use of spectrum in future?

ECC report 249 then proposes measurements with typical equipment and includes sample measurements of different communication systems. The sample measurements outperform the limits of the specifications, in line with the FRMCS lab measurements in (9). On the other hand, the specified limits are those that equipment needs to comply with, also future equipment. Measurements only show the performance of dedicated devices under the measurement conditions.

In the measurement setup, focus was to set up a worst-case environment, bringing the interferer in a state to use all resource blocks and the highest power level, a state that in the field corresponds to a UE at the margin of a cell's coverage trying to get max. throughput transmitted without sharing resource blocks with other devices in the network. The FRMCS UE on the other hand was also brough into a worst-case situation getting a RX power level close to the sensitivity level. In the field this might also be a rare situation, especially as FRMCS will possibly need to be planned in a UL orientated way, which normally leads to a higher DL power level even in the handover regions.

On the other side FRMCS is a critical communication system for railway operation. Relevant interferences might lead to severe affection of railway operation and debugging interference effects in running mobile operations is not a situation anyone wants to face. Other than public bands, that can normally move the data transfer to other frequency bands if one is affected from interferences, FRMCS has only very limited possibilities as only two bands are available and n100 at the first stage might be occupied by GSM-R and can possibly only used at a later stage.

Band combinations	Calculation	Simulation	Measurement	Proposed isolation value	Notes on derivation of onboard isolation values
n20 --> n100 (blocking)	60		36	45	20/28 didn't show difference in the Labtest, n20 in Range 2, n28 in Range 3 (ETSI TS 138 101-1: Table 7.6.3-2), n8 UL is much closer to n100 with 51dB calc., 45 seems reasonable
n28 --> n100 (blocking)	45		36	45	value from calculation
n8 --> n100 (Blocking)	51		35	51	value from calculation
n8 --> n100 (OoB)	92	73	50	73	value from simulation, diplexer is needed for all full duplex modems, not device specific
n3/n7 --> n101 (blocking)	45		11,5	45	value from calculation
n78 --> n101 (blocking)	45			45	value from calculation
n1 --> n101 (Blocking)	64		36,5	64	value from calculation
n1 --> n101 (OoB)	89	73	48,5	73	value from simulation, diplexer is needed for all full duplex modems, not device specific

Table 12: Proposed isolation values and derivation.

Table 12 compares calculation results from section 3.1, the results of the duplexer simulation from section 3.2 and the lab test results from section 3.3. Then it proposes an isolation value to be used

for setups with parallel MNO/RMR usage. The proposed isolation values are derived considering the different sources as stated in the notes.

An analysis on the feasibility of modem deployment with the proposed isolation values on a train with different modem variants and frequency bands is included in section 5.3.

4 TRAIN SPECIFIC IMPLEMENTATION ASPECTS

Normally modems will be installed on the train and connected to roof antennas via coaxial cables. Some examples of possible FRMCS installations are given in (11).

The place available on a train roof to install antennas is limited, it is particularly the case for double-decks train due to dynamic gauge. On a train roof, there are several components such as circuit breaker, air conditioning, power converter and pantograph. Between these components there are some “holes” that can be used to install antennas.

The optimal place for an antenna is over the train driver cab, but maximum two antennas can be installed in this area.

Figure 19 shows a train roof configuration with antennas installed in front of the train and between two components such as circuit breaker and air conditioning.

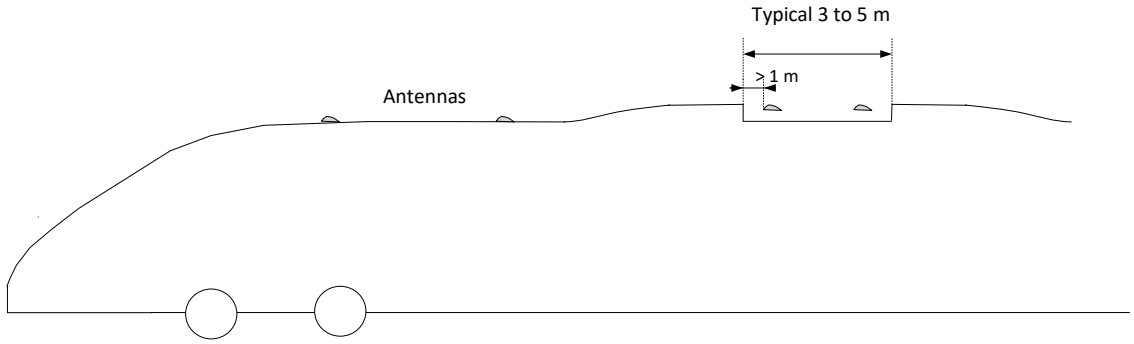


Figure 19: Typical train roof configuration

It is important to note that the top of an antenna cannot be above the dynamic gauge and must be installed at a minimum distance of one meter from any metallic wall.

The next figure shows a typical area on train roof between two components where antennas can be installed.

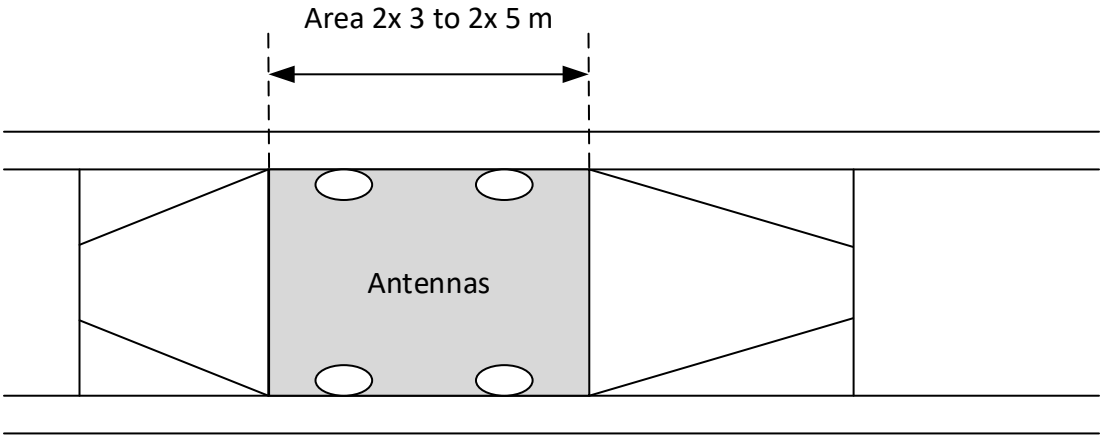


Figure 20: Typical area on a train where antennas can be installed.

Installing antennas on a train roof is never easy. It is the case with passenger trains and even more difficult on yellow trains and shunting locomotives for which the available place is smaller than for passenger trains.

For minimum isolation analysis between antennas installed on train roof distance below 2 m between antennas must be considered.

4.1 EXAMPLE OF AN ISOLATION CALCULATION

The isolation between the antennas can be calculated as follows:

Isolation = FSL (dB)+cable loss(dB) + connector loss(dB) + filter loss(dB) - antenna gain(dBi)



Figure 21: Components taken into account for the calculation of the isolation between antennas on a train.

Free-Space-Loss (FSL) is the frequency dependent signal-loss in free-space. Due to obstacles on the train roof and the influence of the (mostly) metallic train roof the measured isolation between two antennas might deviate from the FSL values. Multiple measurements done for GSM-R at 900 MHz show a slightly lower isolation than FSL between antennas on a train roof (12). For this example, calculation and study, FSL was assumed. Table: 13 gives some examples of free space loss at different distances and frequencies.

Antenna distance	2 m	5 m	10 m
FSL @900MHz	37,5 dB	45 dB	51 dB
FSL @1900MHz	44 dB	51 dB	58 dB

Table: 13: Free space loss examples

Cable losses highly depend on the diameter of the cable and the frequency. As train installations are often 'complicated' often a mixture of ½ inch cables and jumper cables to cross enclosures etc. are necessary.

As an example, the following attenuation levels for cable, connectors, filters etc. will be used:

	Attenuation (cables, connectors, filters, both sides)	Free space loss @2 m distance	Isolation between 2 Modems (2m antenna distance)
900MHz	3 dB	37,5 dB	40,5 dB
1900MHz	5 dB	44 dB	49 dB

The numbers here shall be considered as an example for typical installations for evaluation of the feasibility of certain concepts. The details need to be calculated specifically within the engineering process of the dedicated installation.

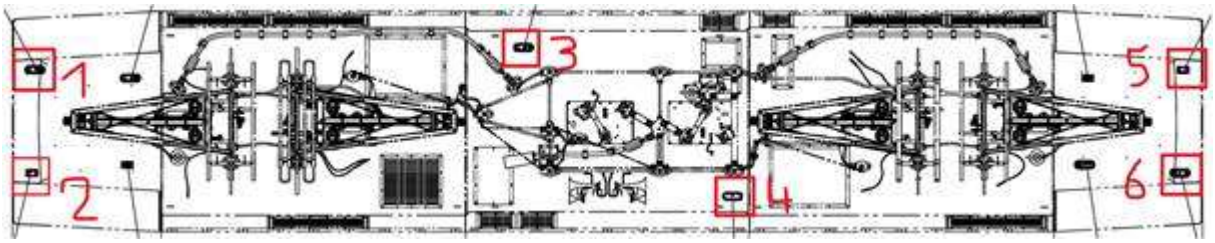
4.2 ISOLATION MEASUREMENTS BETWEEN ANTENNAS ON A VECTRON

Isolation measurements on many different roofs over the last years have shown, that the roof decreases the attenuation between the antennas compared to FSL (12). These measurements were done at 900 MHz only. To have a clear view on the effects on a vehicle roof over the full range of frequency bands, used for FRMCS, measurements were done on different types of vehicles. This chapter summarizes the results of the measurements at:

- Vectron Multisystem (“VectronMS”)
- CabTrain “Vectouro”

4.2.1 VectronMS

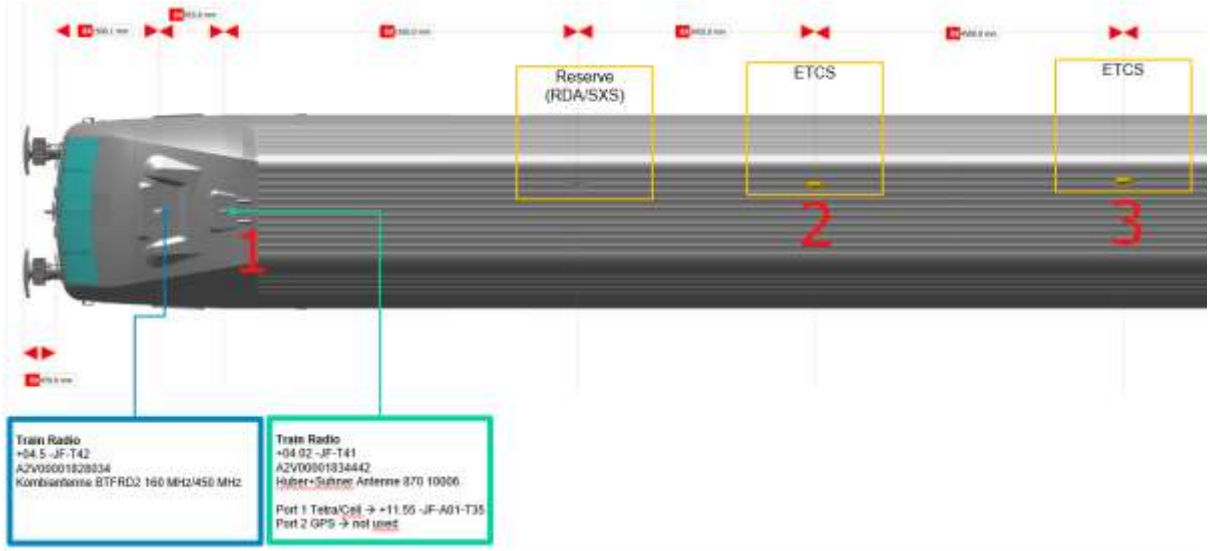
The following figure shows the placement of the different antennas on the VectronMS:



The Vectron was equipped with an ETCS signaling system, a CabRadio and a diagnosis system with remote access. Additional Antennas were installed at possible positions for FRMCS antennas. All places were equipped with broadband antennas, except the CabRadio (Place 5, 450/900MHz antenna). All result of the measurement can be found in (13).

4.2.2 Vectouro

The Vectouro is a CabTrain and equipped ETCS (broadband) and CabRadio (450/900 MHz).



The roof is plane but stiffened with rips. Measurements in the past have shown an influence on the attenuation between the antennas.

4.2.3 Observation

The following colours will be used in the diagrams:

- Blue: The measured values
- Green: Free Space Loss
- Violett: Calculated isolation, based on experiences of older roof measurements on different vehicles (12)
- Red: The idealisation of the measured values excluding special effects

The following two measurements are done between two antennas without obstacles between. The measurement between antenna 5 and 6 is done in the range of 425-925 MHz and shows a decreasing of the isolation by about 4.5 dB.

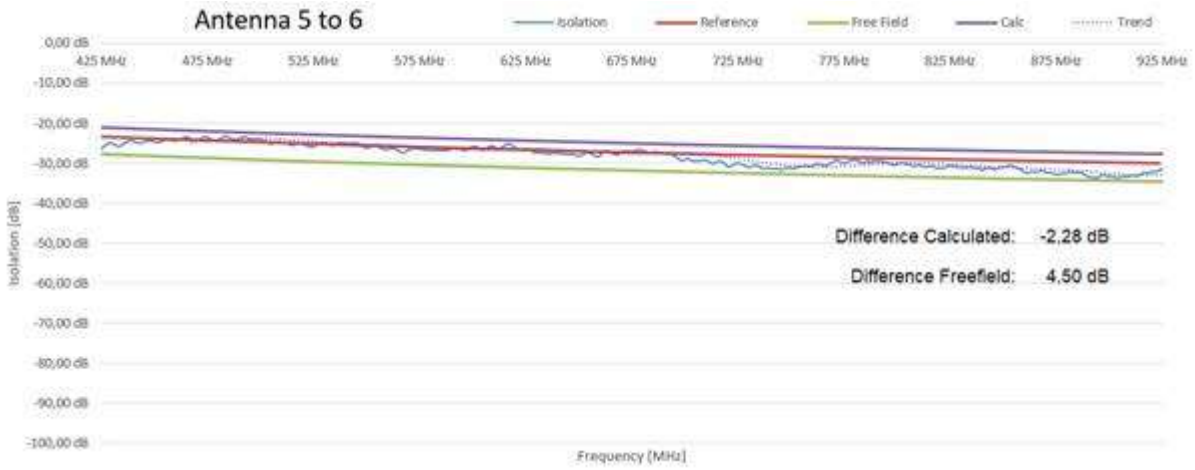


Figure 22: VectronMS, Antenna 5 to Antenna 6, Distance 1.37 m

For antenna 1 and 2 the range could be extended to 4 GHz and shows additional fading effects at frequencies higher about 1.3 GHz. They will be caused by reflection on the roof train inverting the phase of the signal and cause 5-10 dB attenuation at the maxima and up to 40 dB at the singularly points. The fading can go lost as seen in the rage of 3.2-3.7 GHz.

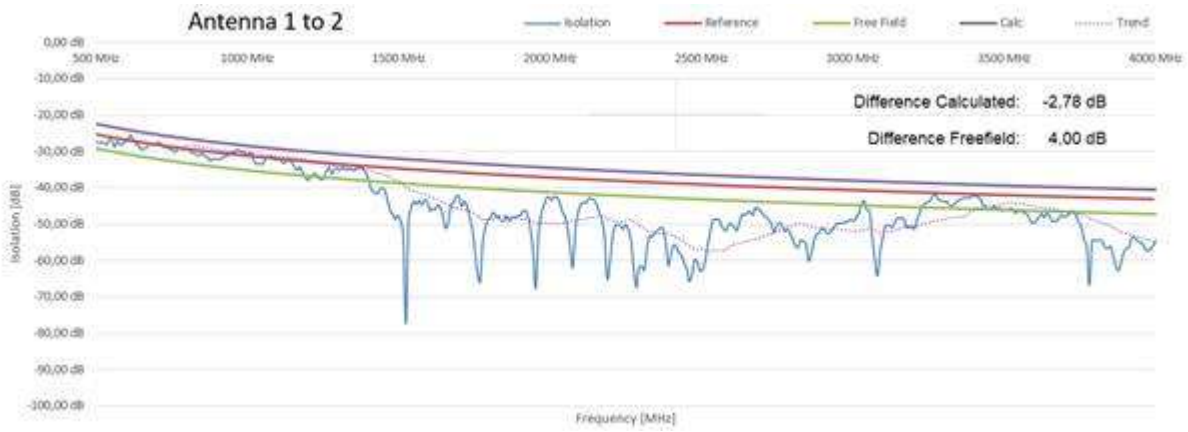


Figure 23: VectronMS, Antenna 1 to Antenna 2, Distance 1.37 m

Crossing pantographs cause a high attenuation of 18-20 dB.

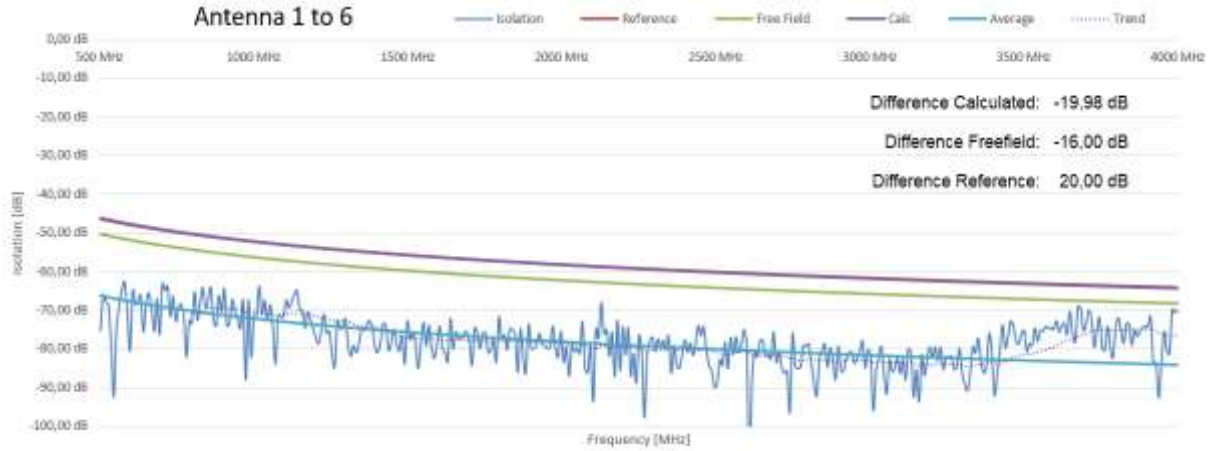


Figure 24: VectronMS, Antenna 1 to Antenna 6, Distance 15.47 m

Passing by the pantographs (clear line of sight) cause up to 16 dB loss.

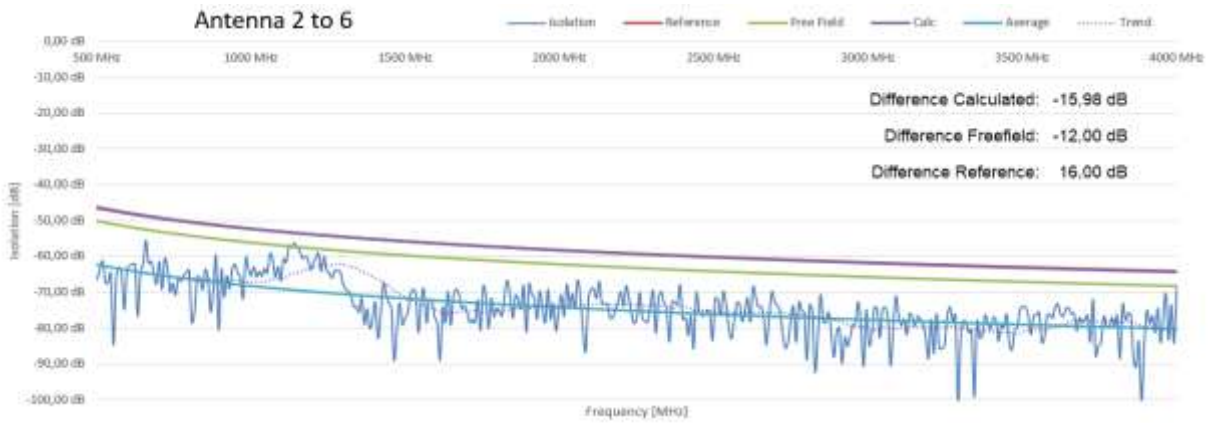


Figure 25: VectronMS, Antenna 2 to Antenna 6, Distance 15.41 m

The signal attenuation when crossing the pantograph can be omitted depending on frequency.

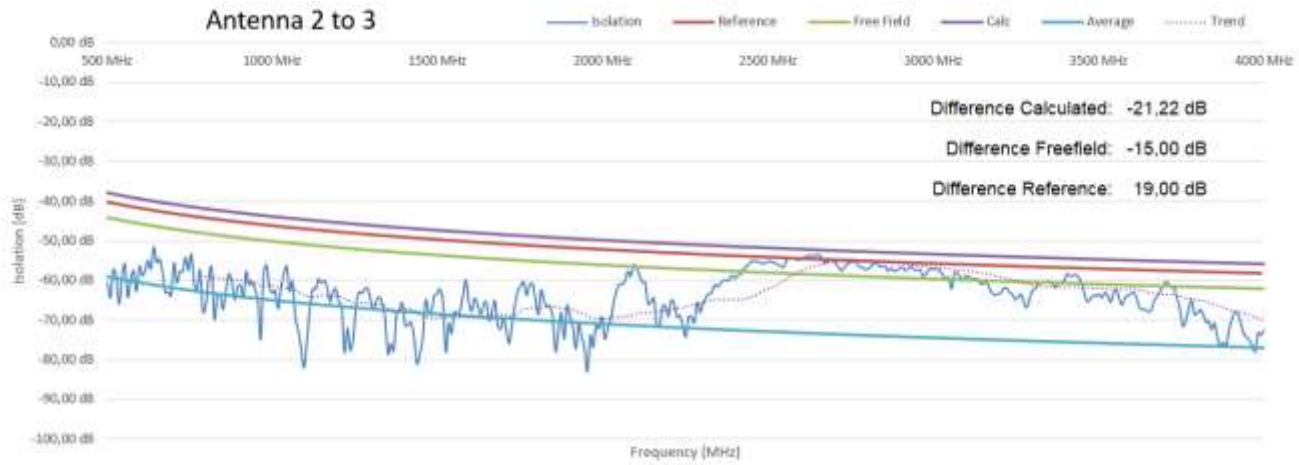


Figure 26: VectronMS, Antenna 2 to Antenna 3, Distance 7.64 m

Crossing rips decrease the attenuation up to 10 dB, 5 dB more than calculated:

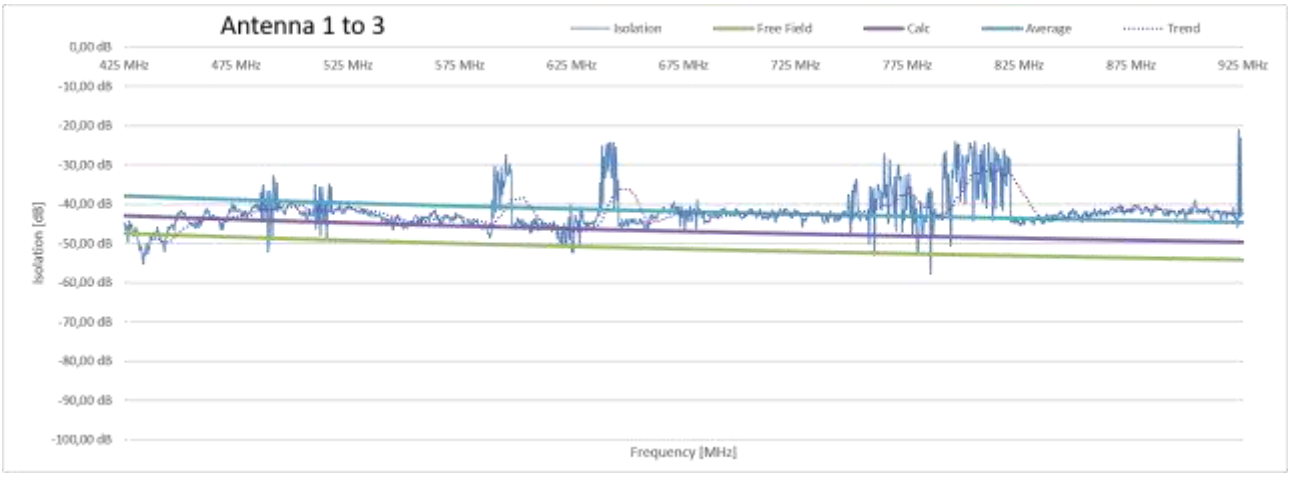


Figure 27: Vectouro, Antenna 2 to Antenna 3, Distance 13.13 m (noise caused by mobile networks in surrounding)

This over increasing was not to be seen, if the rips are not crossed:

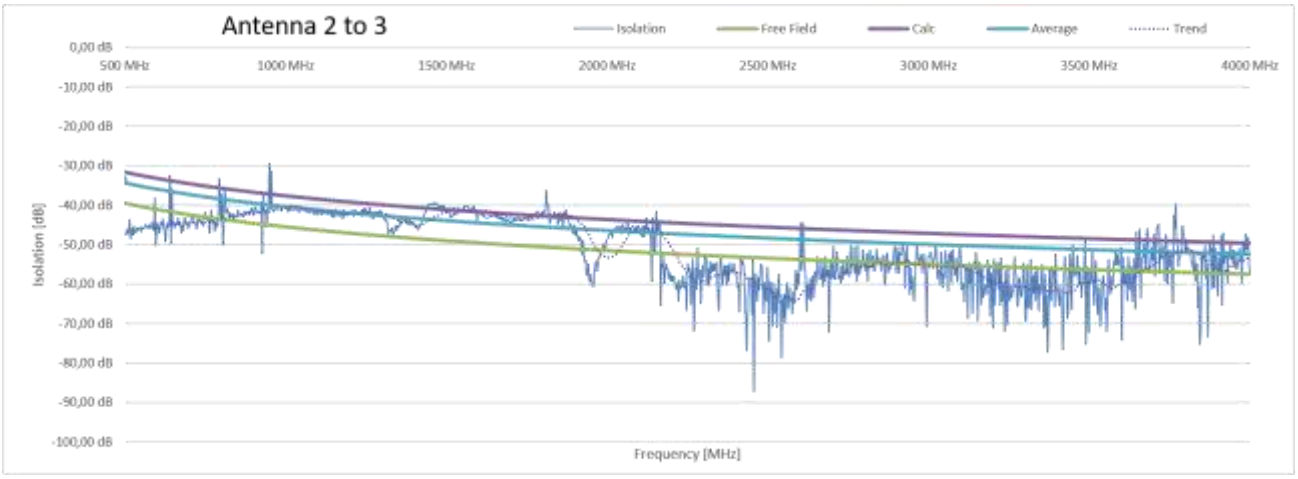


Figure 28: Vectouro, Antenna 2 to Antenna 3, Distance 7.64 m

4.2.4 Conclusions

- The closed metal surface of the roof decrease the attenuation between the antennas by up to 8 dB.
- The curve in (12) describe the attenuation on the roof with a small margin.
- Rips on the roof can decrease the attenuation up to 5 dB additionally.

4.3 TRAIN ROOF IMPACT ON ANTENNA RADIATION

The measurement of the attenuation between the antenna crossing and especially passing the pantographs highlights new aspect: Which influence have the roof of the vehicle to the radio waves propagation. According to (14) isotropic antennas should be used on the train, what should cause an omnidirectional pattern around the train. But what is the real influence of the equipment and the material of the roof on it?

For the measurement on vehicles described in 4.2 the attenuation of significant antennas compared to a reference antenna was/will be done:

- Measurement over slightly more than a quarter circle with a radius of 23 m around the reference antenna 2. Measurement points were defined at 6° intervals.
- Reference antenna has a clear line of sight to all measurement points.
- Path crossing obstacles are excluded from the analysis.
- The external Yagi antenna, equipped with a 900 MHz transmitter, was positioned at a height of 4 m at each measurement point.
- The received signal level was determined using a spectrum analyser.
- The measured values were corrected by the FSL relation to make they comparable.
- Result for each significant antenna is the difference of the attenuation – the deviation - to the reference antenna.

The following figures show the result for Antenna 3 and 6 of the VectronMS:

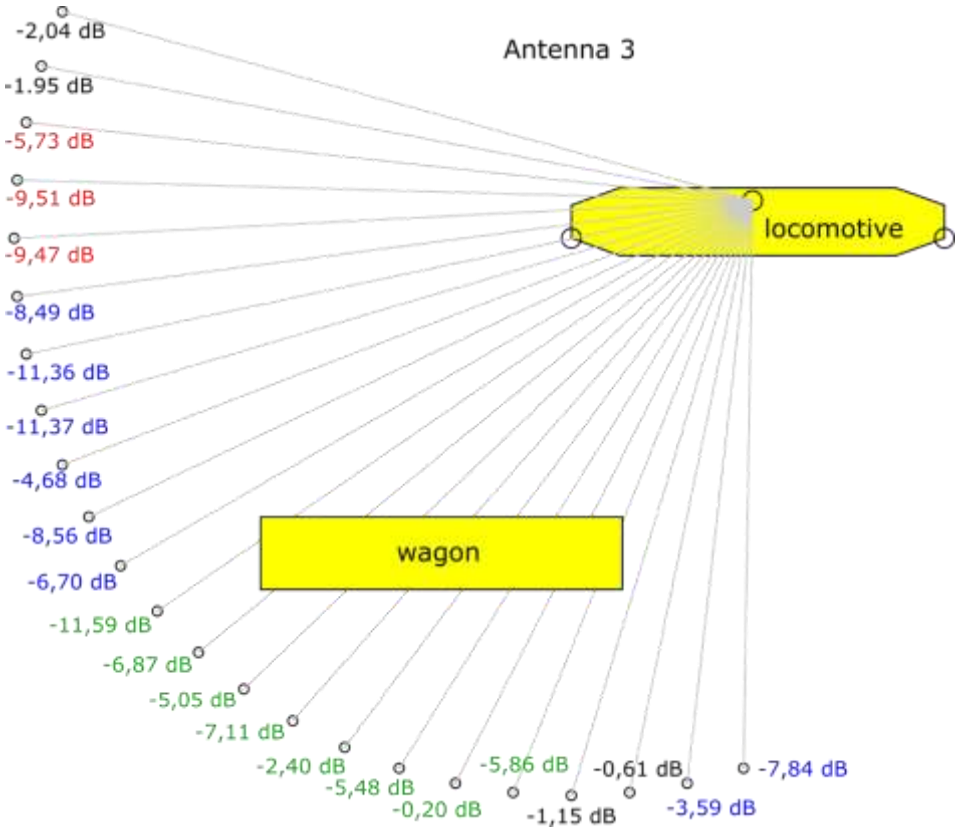


Figure 29: VectronMS, Deviation of Antenna 3 (reference Antenna 2)

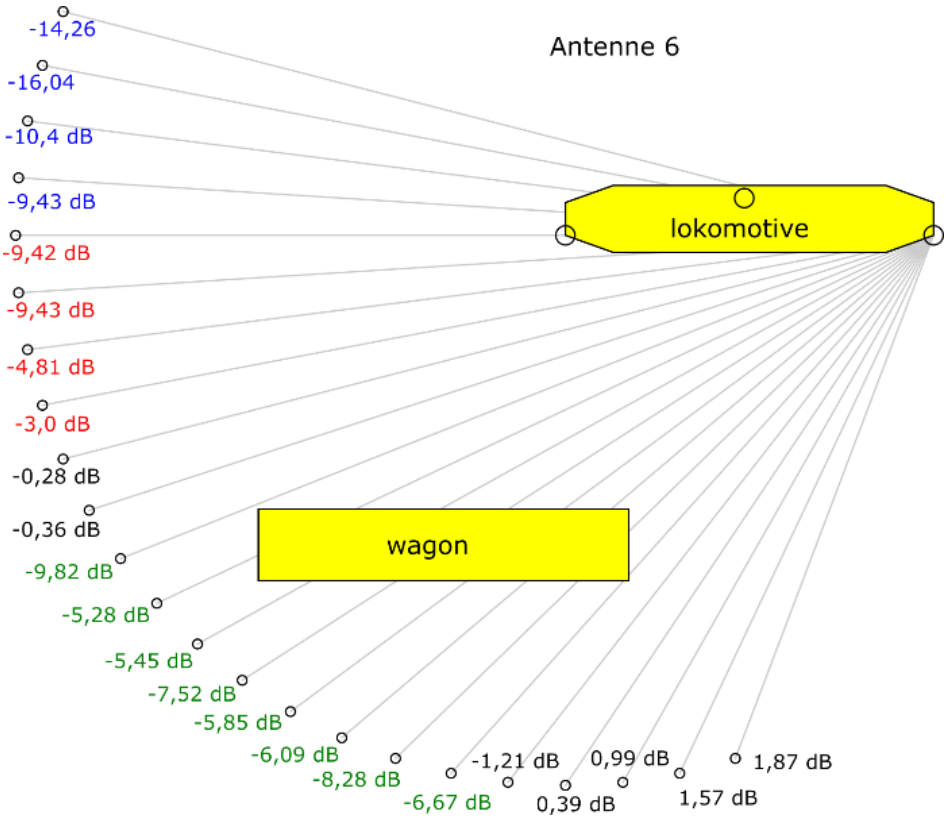


Figure 30: VectronMS, Deviation of Antenna 6 (reference Antenna 2)

The green values were not analysed because of the influence of the wagon, black values show no additional attenuation and blue values are expected by the obstacles of the pantographs.

Interesting are the red values: Although there is a clear view between the antennas a significant attenuation of up to 9 dB is to be seen. The influence is registered in an angle of 12° to 18°.

Further analysis of this topic is recommended.

5 STUDY OF ONBOARD CONCEPT VARIANTS AND USED FREQUENCY BANDS

5.1 MODEM VARIANTS WITH COMBINED AND SEPARATE RMR AND MNO RADIO MODULES

Table 14: FRMCS Modem variants with combined RMR and MNO modems gives an overview on variants with combined RMR and MNO modems. Switching between RMR and MNO could be done via Roaming, eSIM profile switching or MOCN. The way of switching is not relevant for this analysis.

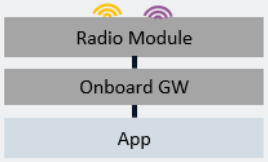
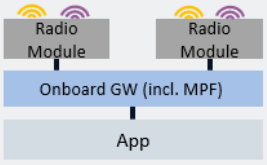
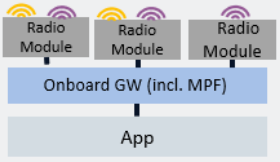
	Variant 1: 1 radio	Variant 2: 2 radios	Variant 3: 3 radios
Architecture RMR freq. bands MNO freq. bands			
Description	1 radio module with 1 physical SIM (RMR + MNO-frequencies)	2 radio modules 2 SIM (RMR + MNO-frequencies)	2 radio modules (RMR + MNO), 2 OB-GWs incl. MPF
Use cases	Cab radio installations	Cab radio + ETCS (and other app)	Cab radio + ETCS (and other app)
Simultaneous connection	RMR or MNO frequency bands only	2x RMR or 2x MNO or mixed	2x RMR or 3x MNO or mixed
Comments			Complex setup, not recommended

Table 14: FRMCS Modem variants with combined RMR and MNO modems

As Variant 3 is not recommended, the Variant 1 and 2 will be further analysed.

Table 15 gives an overview on variants with combined RMR and MNO modems. As Variant 6 is not recommended, further analysis will be done with Variant 4 and 5.

Variants	Variant 4: 2 radio	Variant 5: 3 radios	Variant 6: 4 radios
Architecture			
Description	1 radio module RMR, 1 radio module MNO	2 radio modules RMR, 1 radio module MNO	2 radio modules RMR, 1 radio module MNO
Use cases	Cab radio installations	Cab radio + ETCS (and other app)	Cab radio + ETCS (and other app)
Simultaneous connection	RMR and MNO frequency bands	2x RMR and 1x MNO (no BX with 2x MNO)	2x RMR or 2x MNO or mixed
Comments			Complex setup, not recommended

.

Table 15: Variants with separate RMR and MNO radio modules.

5.2 CONCEPT STUDY WITH CALCULATED ISOLATION VALUES

A concept study with the calculated isolation values is done with modems at 2 m distance as described in chapter 4.1. The relevant isolation requirements are given in Table 16

Band	2m FSL	Cable loss	Isolation (FSL+cables)	Isolation necessary	Isolation necessary through additional filter, rx hardening etc.
n100	37,5 dB	3dB	40,5dB	MNO clean bands → RMR: 61 dB MNO all bands → RMR: 88 dB (n8 → n100))	20.5dB 47.5dB
n101	44 dB	5dB	49dB	MNO clean bands → RMR: 61 dB MNO all bands → RMR: 93 dB (n1 → n101)	12 dB 44 dB

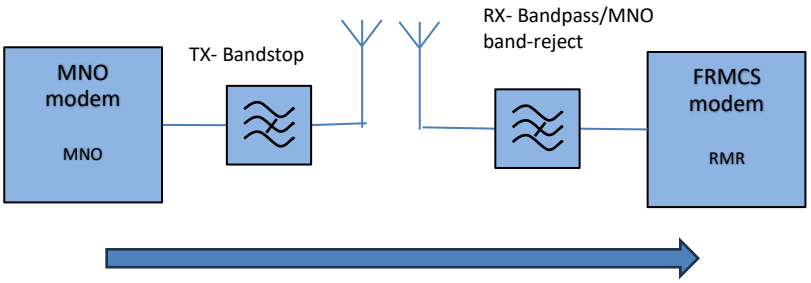
Table 16: Isolation requirements for the concept study with calculated values.

5.2.1 RMR – MNO separate modems

Example Modems at 2 m distance.

With this setup filters could be inserted between Modem and antenna.

Possible setups:



Depending on the amount of RX/TX path in the modems multiple filters would be required. Additional path loss of the filters would need to be considered. Filters are commercially available with the required properties.

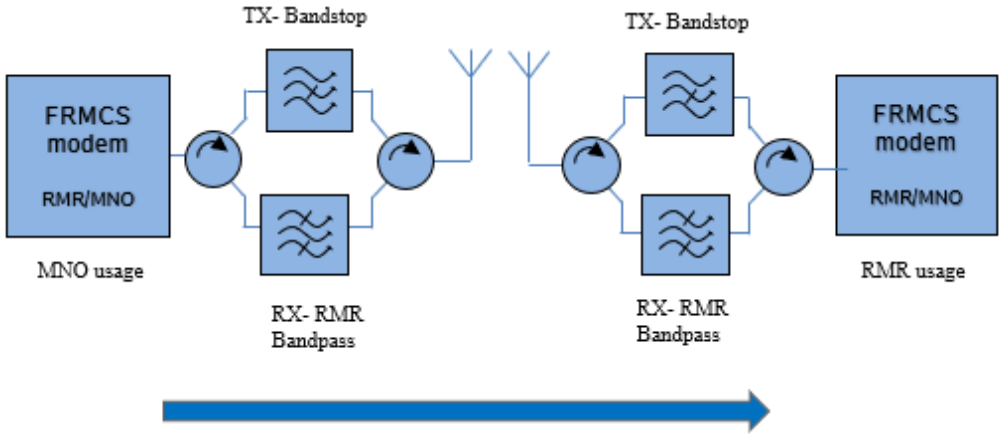
Would work for all bands.

Only ‘clean’ bands → Spurious domain

5.2.2 RMR – MNO combined modem

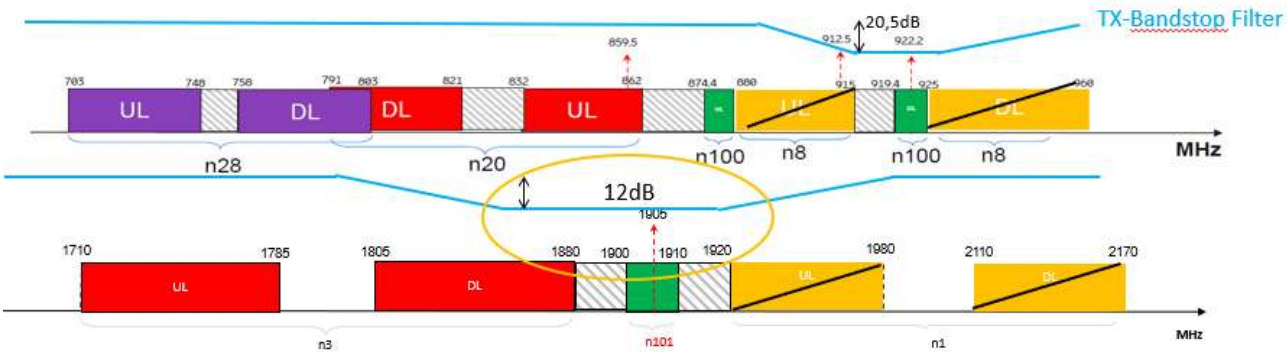
Filter integration between modem and antenna is not easily possible as all frequency bands need to be supported, dependency on the modem architecture.

Possible setup: Modem 1 on the left transmits in public bands, modem 2 receives in RMR bands.



5.2.2.1 Without n1 and n8

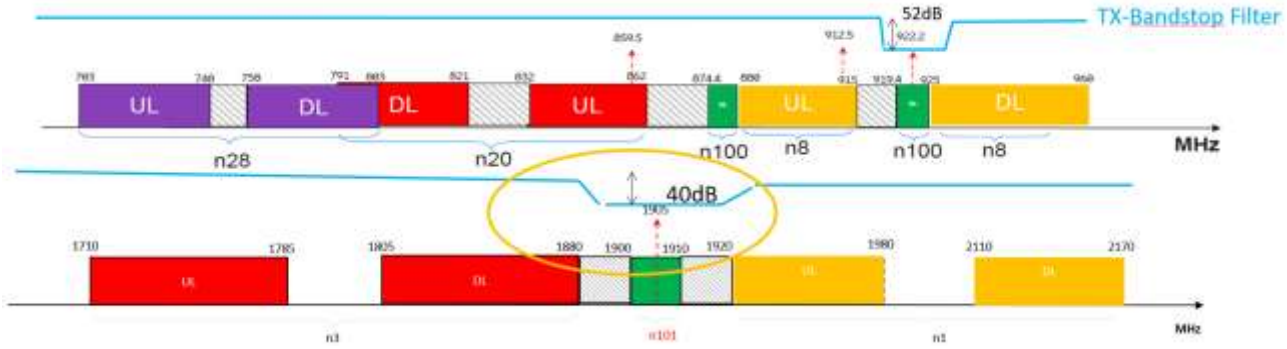
Using only the clean frequencies would need some filtering considering the worst-case calculations



12 dB at n101 difficult as TDD.

5.2.2.2 All frequencies

Using all frequency bands filter requirements are very high, feasibility questionable.



5.2.3 Summary onboard concepts with calculated values

Table 17 gives an overview on the different onboard variants in combination with different frequency bands.

Variant	Frequency bands	Feasibility	Filter	Implementation effort
RMR MNO <u>separate</u> Modem	‘clean’ bands Possible limited coverage/handover relations	Good feasibility	Filters needed with low requirements, good potential to avoid filter with additional studies	High due to additional modem + cables + antennas installation. More flexibility due to lower isolation requirements.
	‘clean’ bands and n8 Good coverage as all low bands are included	good	Potential that filter requirements are lower due to diplexer	High due to additional modem + cables + antennas installation and filter
	all bands full coverage of MNO bands	Good feasibility	Filters with high requirements needed	Very high due to additional modem + cables + antennas installation + additional filters
RMR MNO <u>combined</u> Modem	‘clean’ bands Possible limited coverage/handover relations	Potentially good feasibility	Filters needed with low requirements, good potential to avoid filter with additional studies	Ok More flexibility due to lower isolation requirements.
	‘clean’ bands and n8 Good coverage as all low bands are included	Potentially good feasibility due to diplexer	Filters needed with low requirements, medium potential to avoid filter with additional studies	Ok
	All bands full coverage of MNO bands	Potentially difficult feasibility	Filters with high requirements needed, difficult for n101 TDD	Ok

Table 17: Summary onboard variants with calculated isolation values

5.3 CONCEPT STUDY WITH PROPOSED ISOLATION VALUES

Repeating the concept study with 2 m antenna distance with the proposed isolation values from section 3.4 leads to the results given in Table 18.

Band combinations	Proposed isolation value	2m FSL [dB]	Cable loss [dB]	Iso (FSL+ cables) [dB]	Add. isolation necessary	Filter/other solution	Comments
n20 --> n100 (blocking)	45	37,5	3	40,5	4,5	filter at RMR RX/ RX hardening	very low filter requirements, RX hardening possibly working, then no additional filters necessary
n28 --> n100 (blocking)	45				4,5	filter at RMR RX/ RX hardening	very low filter requirements, RX hardening possibly working, then no additional filters necessary
n8 → n100 (Blocking)	51				10,5	filter at RMR RX/ RX hardening	Combined modems: more comlexity
n8 → n100 (OoB)	73				32,5	filter at MNO TX	Combined modems: more comlexity Separate modems: additional filters for all MNO TX path
n3/n7 → n101 (blocking)	45	44	5	49	-4	no filter needed	
n78 → n101 (blocking)	45				-4	no filter needed	
n1 → n101 (Blocking)	64				15	filter at RMR RX/ RX hardening	Combined modems: more comlexity
n1 → n101 (OoB)	73				24	filter at MNO TX	Combined modems: more comlexity Separate modems: additional filters for all MNO TX path

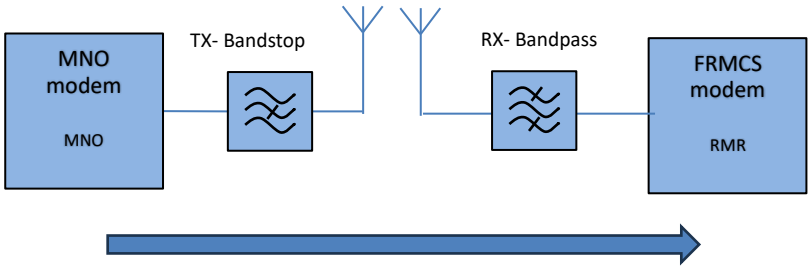
Table 18: 2m concept study with proposed isolation values

Additional isolation is needed for certain band combinations, depending on the interference mechanism (OoB/blocking), filters need to be applied at different locations. For blocking, the RMR receiver needs to be protected from the power of the MNO Uplink. For Out-of-Band emissions falling into the RMR Downlink, those emissions need to be filtered out at the MNO TX side.

RMR – MNO separate modems

With this setup, filters could be inserted between the modem and antenna.

Possible setup for the protection of the RMR Modem:



Depending on the amount of RX/TX path in the modems multiple filters would be required. Additional path loss of the filters needs to be considered. Filters are commercially available with the required

properties. Would work for all bands but high implementation effort, especially n1/n8 usage would lead to additional filters at the MNO TX output.

N100:

For n8 –> n100:

- TX Bandstop Filter needed at MNO Modem with 33 dB attenuation
- RX Bandpass needed with 12 dB attenuation

For n28/n20 (without n8) –> n100:

- Only RX Bandpass needed with 5 dB attenuation

N101:

For n1 → n101:

- TX Bandstop Filter needed at MNO Modem with 24 dB attenuation
- RX Bandpass needed with 15 dB attenuation

For n3/n7/n78 (without n1) –> n101:

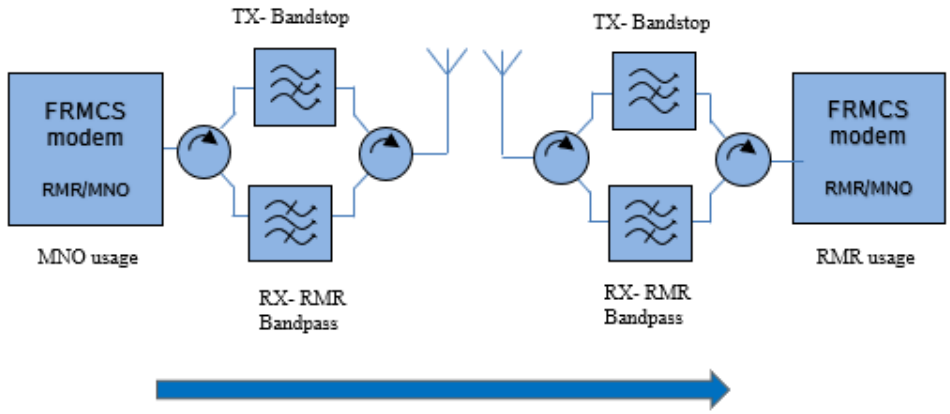
- No additional filters needed

5.3.1 RMR – MNO combined modem

In a combined modem RMR and MNO bands are integrated into the same modem. Assumption is that they can switch between RMR usage and MNO usage (via Roaming or SIM switching) but no parallel operation RMR and MNO at the same time in one modem is possible. The scenario here is that one modem is connected to the MNO network and a second one on the train in parallel to the RMR network. But both are capable of switching the networks and need to support all bands.

Filter integration between modem and antenna is not easily possible and depends on the modem architecture.

A possible setup with circulators: Modem 1 on the left is transmitting in public bands, modem 2 on the right side in reception mode in RMR bands.



For n8 –> n100:

- TX Bandstop Filter needed at MNO Modem with 33 dB attenuation
- RX Bandpass needed with 12 dB attenuation

For n28/n20 (without n8) –> n100:

- Only RX Bandpass needed with 5 dB attenuation

N101:

For n1 → n101:

- TX Bandstop Filter needed at MNO Modem with 24 dB attenuation
- RX Bandpass needed with 15 dB attenuation

For n3/n7/n78 (without n1) –> n101:

- No additional filters needed

.

5.3.2 Summary onboard concepts with proposed values

Frequency bands	Modem variant	Implementation effort	Coverage	Feasibility	comments/ open topics
All bands (n28, n20, n8, n3, n1, n7, n78)	separate	Very high (additional modems, antennas, filters at MNO TX and RMR RX)	very good	good	
	comb.	high (filters, circulators)		questionable	filter for TDD difficult
All bands without n1	separate	Very high (additional modems, antennas, filters)	good (all low bands included)	good	
	comb.	high (filter, circulator)		possibly good, but high integration effort due to circulators, filters etc.	
All bands without n1 and n8	separate	high (additional modems, antennas)	Could be limited depend. on 5G rollout plans, still n7, n28 as low bands	Good	
	comb.	medium		good	

Table 19: Summary onboard deployment feasibility

6 MIGRATION SCENARIOS FROM GSM-R TO FRMCS

The migration period from GSM-R to FRMCS will be challenging as different systems might run in parallel on a train. Relevant for this study is especially when the migration to FRMCS of different applications on a train is not aligned. This might lead to parallel usage of GSM-R and FRMCS/MNO systems on one train. For this scenario coexistence analysis needs to be done, as for example an 8W GSM-R Modem might lead to blocking effects in an FRMCS modem if too close together and running in parallel.

6.1 TRANSITIONS BETWEEN FRMCS AND GSM-R ON A TRAIN

The FRMCS SRS (6) defines different transitions in the following chapters/sections:

10.1.4: GSM-R to FRMCS Transition for On-Board FRMCS

10.1.5: FRMCS to GSM-R Transition

And specifically for Voice Applications (VAS):

24.2.6.3: Transition from/to FRMCS to/from GSM-R mode of operation

It defines a manual switch mode that is not synchronized with the transition of ATP (ETCS)/ATO communication.

Note 10 states: The procedure assumes sufficient coverage overlap to ensure the deregistration can be performed before the FRMCS coverage ends. De-registration of FRMCS IDs under GSM-R coverage via IWF would be a more robust approach.

Note 11 states: The procedure assumes sufficient coverage overlap to ensure the deregistration can be performed before the GSM-R coverage ends. De-registration of GSM-R FNs under FRMCS coverage via IWF would be a more robust approach.

6.2 PARALLEL OPERATION OF FRMCS AND GSM-R ON A TRAIN

For further study of the migration scenarios, it makes sense to distinguish between trains with only cabradio installations and trains with cabradio and ETCS.

For only cabradio trains parallel operation of FRMCS and GSM-R might only take place within the transition zone/time. For trains equipped with cab radio and ETCS, both FRMCS and GSM-R may operate in parallel over an entire section of track. This can happen, for example, when the FRMCS

network is already being used for voice communication, but the Radio Block Centre (RBC) in that section has not yet been upgraded to support FRMCS.

6.3 LIST OF SCENARIOS CONSIDERED

For the migration different scenarios need to be considered as described in (15).

The following scenarios are considered in this study:

Scenario A: Migration using the 900 MHz band: simultaneous operation of both GSM-R and FRMCS in the 900 MHz band.

Scenario B: The migration will take place using the 1900 MHz frequency band n101 and continued operation of GSM-R in the 900 MHz band. After the migration period, the GSM-R network will be switched-off and FRMCS will be deployed in 900 MHz frequency band n100 and 1900 MHz band n101.

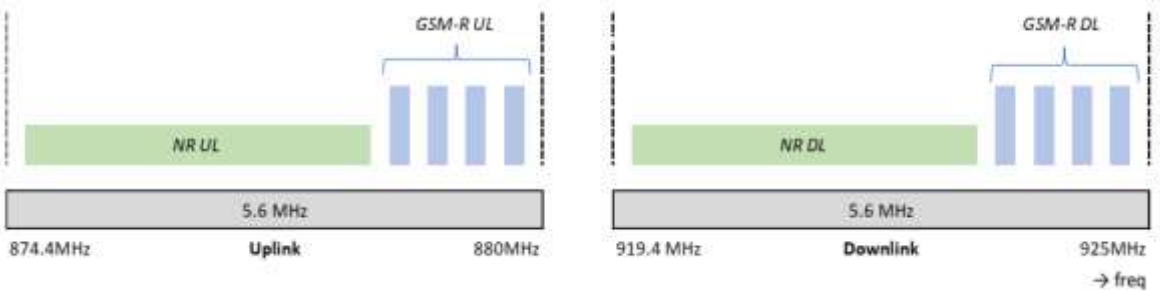
Scenario C: Migration using both 900 MHz and 1900 MHz bands: simultaneous operation of both GSM-R and FRMCS in the 900 MHz band plus FRMCS in the 1900 MHz band.

6.3.1 Minimum isolation requirement for the Scenario A

The migration for the scenario A can be implemented considering two approaches:

- 5G NR n100 (FRMCS 900) with a channel bandwidth of 3 MHz instead of 5 MHz
- 5G NR n100 overlay to GSM-R

The next figure from (15) shows the planned frequency arrangement for the first approach.



The RMR modem will occupy the first 3 MHz of the 5.6 MHz allocated bandwidth while the higher part of the band will be used by the GSM-R carriers. A minimum guard band of 200 kHz is considered between FRMCS and GSM-R but the exact guard band will be defined in further study.

This approach allows simultaneous operation of FRMCS 900 and GSMR at the condition that isolation between RMR 900 and GSMR modem be high enough to avoid mutual interference.

The isolation requirements for this approach have also been computed by Ericsson in (2). As described in section 3.1 the computation considers several worst-case scenarios, further studies in the lab are recommended.

The isolation requirement for GSMR and FRMCS is summarized in table Table 20: Isolation requirements for GSM-R and FRMCS 900 Table 20.

Aggressor	Victim	Isolation required for Blocking in dB	Isolation Required for unwanted emission in dB	Comments
FRMCS 900	GSMR	57	81	Blocking Level protection: Filter victim side
GSMR	FRMCS 900	90	61	Unwanted emission protection: Filter Aggressor side

Table 20: Isolation requirements for GSM-R and FRMCS 900

To allow simultaneous operation of GSMR and FRMCS 900 for the scenario A, a duplexer will be required between the GSMR modem and its antenna.

The worst case is the isolation required to protect the FRMCS 900 modem from the transmissions of the GSMR modem. An external duplexer will be required between its Rx/Tx RF interface and its antenna and a bandpass filter between its Rx interface and its antenna.

If we consider a rejection of 50 dB that can be easily achieved with a cavity filter to reach 90 dB, a pathloss of 40 dB between antennas is necessary. It means a minimum distance of 3 m between GSMR and FRMCS 900 antenna based on FRIIS formula.

For the second approach based on 5G NR n100 overlay to GSM-R, it is reasonable to assume the same level of isolation is required as a first step without further study.

Important note: The minimum distance of 3 m is indicative and must be assessed with measurements.

6.3.2 Minimum isolation requirement for the Scenario B

The calculated isolation requirements for GSMR and FRMCS 1900 from (2) are summarized in Table 21.

Aggressor	Victim	Isolation required for Blocking in dB	Isolation Required for unwanted emission in dB	Comments
FRMCS 1900	GSMR	57	57	Blocking + unwanted emissions: Filter on both sides
GSMR	FRMCS 1900	61	40	Blocking Level protection: Filter victim side

Table 21: Isolation requirements for GSM-R and FRMCS 1900

The highest isolation required is 57 dB to protect the GSMR of a FRMCS 1900 modem.

The highest isolation required is 61 dB to protect the FRMCS 1900 modem from GSM-R blocking.

As the frequency bands are quite far away from each other, the respective sensitivity of the modems might be sufficient to allow parallel operations without applying filters. Lab measurements to verify this are recommended.

As after migration FRMCS will be deployed in 900 MHz frequency band n100 and 1900 MHz band n101. If both bands are used within the same 5G network 5G scheduler and internal interference management might be sufficient to avoid interferences. Additionally, also the modem sensitivity might be sufficient for the distant frequency bands.

If calculating the isolation between FRMCS900 and FRMCS 1900 as described in section 3.1, Table: 22 shows the results.

Aggressor	Victim	Isolation required for Blocking in dB	Isolation Required for unwanted emission in dB	Comments
FRMCS 1900	FRMCS 900	48	61	Blocking Level protection: Filter victim side
FRMCS 900	FRMCS 1900	48	56	Unwanted emission protection: Filter Aggressor side

Table: 22 Calculated isolation values between n100 and n101 modems

The highest required isolation is 61 dB to protect FRMCS 900 from unwanted emission issued by FRMCS 1900 modem. An isolation of 56 dB is required to protect FRMCS 1900 from FRMCS 900. With band splitters (diplexer) having 50 dB of isolation, antenna sharing between FRMCS 900 and 1900 could be considered.

The distance between FRMCS 900 and FRMCS 1900 antennas can be minimum 1 m at the condition that external duplexer be installed between the FRMCS 900 modem and its antenna and a band pass filter between the FRMC 1900 modem and its antenna.

Important note: The minimum distance of 1 m is indicative and must be assessed with measurements.

6.3.3 Minimum isolation requirements for the scenario C

The scenario C considers a migration using the GSMR, the FRMCS 900 MHz and the FRMCS 1900 MHz band simultaneously.

GSM-R and FRMCS 900 MHz modems operating simultaneously means that an isolation of 90 dB is required between GSMR and FRMCS 900 modems.

Simultaneous operation of GSMR and FRMCS 1900 modems requires an isolation between GSMR and FRMCS 1900 modems of 57 dB.

Simultaneous operation of FRMCS 900 and FRMCS 1900 requires an isolation between both Radio modems of minimum 56 dB.

Table 23 summarizes the required isolation.

	GSMR	FRMCS 900	FRMCS 1900
GSMR		90 dB	57 dB
FRMCS 900	90 dB		61 dB
FRMCS 1900	61 dB	64 dB	

Table 23: Calculated isolation values for GSM-R and FRMCS n100/n101

A possible solution can be a band splitter with 50 dB rejection allowing sharing of one antenna between FRMCS 900 and FRMCS 1900 modems with a minimum distance between this antenna and the GSMR antenna of 3 m.

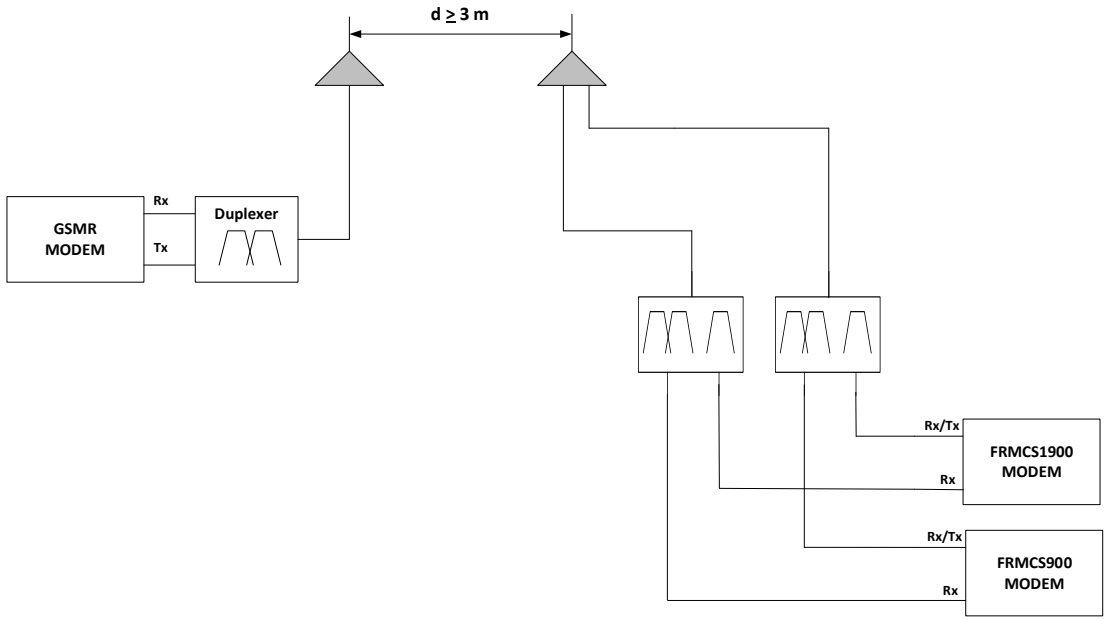


Figure 31: Setup with FRMCS 900/1900 connected to one antenna and GSM-R

Another solution can be GSMR, FRMCS 900 and FRMCS 1900 modems connected to separate antennas via duplexer and band pass filters. The distance between both FRMCS antennas can be 1 m and the distance between each FRMCS antenna and GSMR antenna shall be minimum 3m.

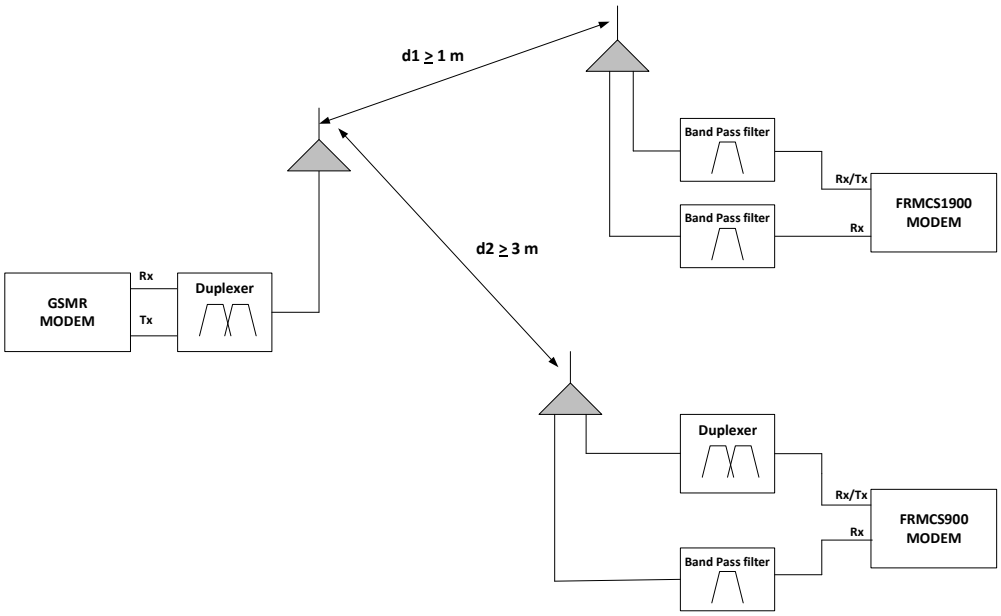


Figure 32: Setup with FRMCS 900/1900 connected to separate antennas and GSM-R

Important note: The minimum distances of 1 m and 3 m are indicative and must be assessed with measurements.

6.4 CONCLUSIONS AND PROPOSED NEXT STEPS FOR GSM-R TO FRMCS ISOLATION

As the comparison between lab test results and calculations between FRMCS and MNO modem is quite significant, lab tests to compare calculations and hardware performance for GSM-R and FRMCS are also recommended and might help to optimize the onboard deployment for the migration period.

Further analysis on the transition procedures from GSM-R to FRMCS and vice versa for the different applications might also help to get further understanding on the onboard requirements.

7 SUMMARY AND CONCLUSIONS

This deliverable investigated the isolation requirements needed for the simultaneous operation of Railway Mobile Radio (RMR) services and public Mobile Network Operator (MNO) services in future FRMCS onboard deployments. The work was motivated by the increasing relevance of hybrid railway communication architectures, where dedicated railway spectrum in the RMR bands may be complemented by public mobile network bearers to improve coverage, resilience, capacity and/or service continuity. In such architecture, several radio systems need to be installed and operated on the same train. This creates a specific coexistence situation that differs from general spectrum sharing studies, because the interfering transmitter and the victim receiver may be located on the same vehicle and can therefore remain permanently close to each other while the train is moving through changing radio conditions. As a critical communication system, interferences that might be acceptable for public broadband services can have a severe effect on railway operation.

The study focused on the protection of the FRMCS RMR bands n100 and n101 when MNO radio modules are operated in parallel onboard. The relevant FRMCS spectrum consists of n100 in the 900 MHz range, operated in FDD mode, and n101 in the 1900 MHz range, operated in TDD mode. The most critical MNO bands are those adjacent to these RMR bands, in particular MNO band n8 towards FRMCS n100 and MNO band n1 towards FRMCS n101. Other MNO bands in the spurious domain, including n20, n28, n3, n7 and n78, were also considered. The analysis deliberately concentrated on interference from MNO uplink transmissions towards FRMCS reception, as this represents the most relevant onboard coexistence case for maintaining reliable railway communication.

Chapter 2 provides the relevant use-cases for hybrid FRMCS networks. Public mobile networks can complement private railway mobile radio by providing additional bearers for fallback, coverage extension, resilience, capacity extension or application-specific data path selection.

A first set of isolation values was derived from coexistence calculations outside of this study, based on radio equipment characteristics from the applicable 3GPP and FRMCS radio specifications with the assumption of worst-case operating conditions (2). The highest calculated isolation requirement for FRMCS n100 as victim was 92 dB, driven by unwanted emissions from MNO band n8. For FRMCS n101 as victim, the highest calculated isolation requirement was 89 dB, driven by unwanted emissions from MNO band n1. For other considered MNO bands, the calculated requirements were significantly lower, typically around 61 dB where the bands are further away and therefore less critical.

The deliverable further analysed the influence of radio modem design, particularly the role of duplexers in FDD systems. The initial worst-case calculations are based on spectrum mask assumptions and do not necessarily reflect the behaviour of radio modems optimised for full-duplex FDD operation of the interfering system. Simulations of representative 5G NR transmission chains showed that internal duplexers, necessary for full-duplex FDD operation, can significantly reduce unwanted emissions into the receiver path. For the n8 case towards FRMCS n100, the required

isolation reduces from 92 dB to approximately 73 dB when a modem with an internal duplexer is assumed. A similar result was obtained for the n1 case towards FRMCS n101, where the required isolation also reduces to approximately 73 dB. This indicates that modem implementation details have a strong influence on the practical isolation requirements and should therefore be considered when defining mandatory onboard support of MNO frequency bands.

To validate the calculated and simulated results against real equipment behaviour, laboratory tests were planned and performed using a controlled and reproducible setup with one of the first FRMCS prototype modems available. Public MNO signals from 5 different UEs were recorded with a vector signal generator and analysed for relevant interferences towards the FRMCS n100 uplink and downlink range and the FRMCS n101 range. A 5G base-station simulator was used to generate representative 5G configurations and to control the resource block allocation. The tests showed that the amount of out-of-band emission strongly depends on the used radio configuration. Full resource block allocation close to the relevant band edge represents a worst-case configuration, while reduced resource block allocation leads to considerably lower interference levels. For MNO bands located further away from the RMR bands (spurious domain), no significant signal levels falling into the FRMCS receiving bands were observed in the test results.

As a next step the MNO UE signals were used as interferers to disturb an FRMCS connection that was configured to be close to the sensitivity Rx level, simulating a FRMCS connection at cell edge. With this setup the power level of the interferer was augmented until a measurable impact on the FRMCS throughput could be measured. Tests were performed both with and without band-reject filters for the FRMCS bands. Without filters, out-of-band emissions were expected to dominate for the adjacent bands n8 and n1. With filters, blocking effects were expected to become more relevant. The isolation requirements derived from the lab test results are significantly reduced compared to the calculated values and simulation results.

Band combinations	Calculation	Simulation	Measurement	Proposed isolation value	Notes on derivation of onboard isolation values
n20 --> n100 (blocking)	60		36	45	20/28 didn't show difference in the Labtest, n20 in Range 2, n28 in Range 3 (ETSI TS 138 101-1: Table 7.6.3-2), n8 UL is much closer to n100 with 51dB calc., 45 seems reasonable
n28 --> n100 (blocking)	45		36	45	value from calculation
n8 --> n100 (Blocking)	51		35	51	value from calculation
n8 --> n100 (OoB)	92	73	50	73	value from simulation, diplexer is needed for all full duplex modems, not device specific
n3/n7 --> n101 (blocking)	45		11,5	45	value from calculation
n78 --> n101 (blocking)	45			45	value from calculation
n1 --> n101 (Blocking)	64		36,5	64	value from calculation
n1 --> n101 (OoB)	89	73	48,5	73	value from simulation, diplexer is needed for all full duplex modems, not device specific

Table 24: Proposed isolation values and derivation.

With calculated values, simulation results and lab test results available, as proposed in ECC report 249 (10), a weighting follows, whether sharing/compatibility studies shall be based on typical performance of unwanted emissions rather than the limits from specifications. A proposal on isolation values is elaborated considering the different sources as given in Table 24.

The train-specific implementation analysis in Chapter 4 highlighted that antenna placement and train roof conditions are decisive for achieving the required isolation in practice. Train onboard radio systems are constrained by available roof space, existing antennas, metallic structures, pantographs, roof equipment and vehicle-specific geometry. The distance and orientation between antennas, as well as the presence of obstacles, directly influence coupling and therefore the achievable isolation. Measurements on train roofs, including the Siemens Vectron example described in the report, provide valuable evidence that actual isolation can vary considerably with antenna position and vehicle layout.

A concept study follows in Chapter 5 to compare different implementation variants, the isolation requirements and the usage of different frequency bands to create a decision base. Taking the train specific implementation aspects into account, a distance of 2 m between the antennas was used for the study. Beside combined RMR and MNO capability within the same radio module, also separated RMR and MNO radio modules were analysed against installation complexity and feasibility. Starting with the calculated isolation values, as a next step, the proposed isolation values were considered in the concept study in section 5.2. It gives a comparative overview on different frequency bands, modem variants, deployment feasibility and complexity. Excluding the adjacent bands n1 and n8 would reduce the complexity of the onboard setup significantly as no filters at the MNO TX would be necessary.

Chapter 6 additionally examines the migration from GSM-R to FRMCS and the additional onboard coexistence challenges that arise when legacy GSM-R and new FRMCS systems operate on the same train. The chapter explains that migration will not always be synchronised across all railway applications. For example, voice services may transition to FRMCS while ETCS/RBC communication still relies on GSM-R, which can lead to extended parallel operation of GSM-R and FRMCS radio systems onboard. This creates a specific isolation challenge, particularly because GSM-R modems can transmit at relatively high power and may cause blocking or unwanted-emission effects in nearby FRMCS receivers. The proposed antenna distances and filtering concepts are again based on calculated worst-case values derived from the specifications. Like the approach used for the MNO coexistence, also for GSM-R/FRMCS coexistence further laboratory testing to compare calculated isolation values with actual modem performance is recommended. Additionally further analysis of the transition procedures for the different onboard applications is recommended.

To summarize this deliverable provides a comprehensive study of different aspect of isolation requirement and deployment options for simultaneous operation of RMR and MNO services as well as first analysis of migration related isolation requirements.

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