4G/5G Performance

Coexistence Study for the Evaluation of LTE/5G FDD and 5G TDD Scenarios

Authors: Dipl. Ing. Thomas Heyn,
Dr. Geordie George

Date: 30.10.2024

Classification: PUBLIC

1 Executive Summary and Conclusion

Goal of this study is to analyse the coexistence of an existing 4G/5G Mobile/Fixed Communication Network (MFCN) and the planned 4G/5G network for trains, called the Future Railway Mobile Communication System (FRMCS), also called the Railway Mobile Radio (RMR) in 3GPP context. Since a significant share of the MFCN sites is located in the vicinity of the railroads, potential interference caused by the new FRMCS system plays a significant role for existing and future deployments of MFCN base stations operating in nearby bands. Likewise, potential interference on the safety-critical FRMCS from the existing MFCN network is relevant as well. Our study examines the conditions under which both networks with small frequency separation can coexist with minimum interference effects.

In the following, all observations and recommendations from the respective detailed subchapters from the study report are summarized:

Observations from ECC report 318 [6]:

Informative key points from the executive summary in ECC report 318 [6] are given below to note the approach and intention of the CEPT evaluation:

- *Only non-AAS FRMCS and non-AAS MFCN systems have been considered. Additional studies should be performed in case AAS systems are considered for FRMCS in the 1900-1910 MHz band. The protection of MFCN 5G/NR with AAS BS above 1920 MHz was not studied in this Report. Further analysis of the interference impact of FRMCS on MFCN AAS systems may be required.*
- *As described in CEPT Report 19, the Block Edge Mask (BEM) is developed for the GSM-R / FRMCS transmitters on the basis that detailed coordination and cooperation agreements would not be required to be in place prior to network deployment. The BEM for the transmitter emissions would not avoid all interference that might arise in certain deployment scenarios, including for some configurations at shared base station sites or between nearby base station sites. In these situations, mobile network operators and RMR operators of both systems may have to coordinate, and the use of additional interference mitigation techniques might be considered.*

Key points noted from the conclusions in [6]:

- With the current level of selectivity of MFCN base stations, the defined Least Restrictive Technical Conditions (LRTC) for FRMCS may result in interference to some MFCN base stations located near FRMCS BS sites. One way of addressing this interference is to coordinate FRMCS and MFCN deployments. However, this means that FRMCS operators may not be able to use +65 dBm at certain locations. **If +65 dBm EIRP for uncoordinated FRMCS base stations is desired, then many MFCN BSs may need to be adapted** when an FRMCS BS is rolled out in their proximity to minimize interference from FRMCS.
- Additional mitigation techniques need to be implemented on a case-by-case basis, such as adjustments of antenna directivity, azimuth, tilt, or improve the selectivity of the MFCN BS in the vicinity of the railway tracks.

- In order to ensure that the MFCN operators have enough time to adapt the relevant radio sites, the RMR operator is required to perform an early notification procedure in advance of the rollout of a new FRMCS BS.
- In order to enable an in-block EIRP of +65 dBm/(10 MHz) for FRMCS BS, the MFCN BS selectivity would need to be 98.3 dB (assuming an Minimum Coupling Loss (MCL) of 63 dB measured at the antenna connector), which is
    - 24.3 dB more selectivity compared that in the CEPT Report 39
    - 40.6 dB more selectivity in compared to that in the 3GPP specification TS 37 104.
- In order to enable an in-block EIRP of +65 dBm/(10 MHz) for FRMCS BS, the MFCN BS selectivity would need to be 88.3 dB (assuming an MCL of 73 dB measured at the antenna connector), which is
    - 14.3 dB more selectivity compared that in the CEPT Report 39
    - 30.6 dB more selectivity in compared to that in the 3GPP TS 37 104.
- The interference from FRMCS cab-radio of +31 dBm output power to MFCN uplink is acceptable according to ECC reports when uplink power-control is implemented and activated.

Observations from 3GPP specification:

- The specified maximum blocking level in 3GPP for base stations is depending on the frequency separation between wanted signal and interfering signal:
    - With at least 20 MHz separation/gap, the allowed blocking level is -15 dBm for a CW interferer.
    - At a separation of maximum 20 MHz, the maximum interfering level is -43 dBm.
- The maximum blocking level specifications are the same for LTE, LTE NB-IoT and 5G NR base stations.
- 3GPP does not specify or intent to specify further enhanced selectivity for FRMCS scenarios as currently introduced for RMR.
- As the blocking levels are depending on the frequency separation between two carriers, the most severe interference we expect from the FRMCS base station on the MFCN Uplink at 1920-1940 MHz, with an allowed blocking level of -43 dBm.
- In opposite direction, the MFCN DL at up to 1880 MHz is separated by 20 MHz from the FRMCS Uplink at 1900-1910 MHz, leading to a higher allowed blocking level by 28 dB, to an absolute power level of -15 dBm.
- The FRMCS cab-radio UE's EIRP of up to +33 dBm (according to ECC report 318 [6]) might lead to temporary interference due to the less spatial separation to the MFCN base stations and the higher time share of UL transmissions (UL:DL ratio 3 in FRMCS TDD configuration according to ECC report 314 [5])
- The dominant interference source with a frequency separation of 10 MHz is the carrier signal level of FRMCS of up to +65 dBm EIRP, being dominant over the interference by out-of-band emissions of the FRMCS carrier.
- We assume the maximum allowed blocking level for base stations as the primary source for potential interference in coexistence scenarios of MFCN and the future FRMCS.

Main interference on the MFCN Uplink is expected by

- The carrier signals of the permanently present FRMCS base stations.
- The temporary interfering UE cab radios with quasi-omnidirectional antenna pattern
    - with a EIRP 32 dB lower than FRMCS gNB

- but with a lower distance than the FRMCS base stations,
- and with a greater time share of UL transmissions, compared to the DL transmissions of the FRMCS gNB (UL:DL is 3:1 according to [5])

Recommendations from 3GPP specifications:

- For interference analysis- in coexistence scenarios of FRMCS and MFCN in Band 1, a maximum blocking level of -43 dBm as specified by 3GPP should be used.
- Further interference mitigation is essentially required especially in uncoordinated deployments.
- In the 3GPP specifications related to the new band n101 for FRMCS, measures to minimize interference on MFCN UL in band 1/n1 shall be considered. This is especially true for the new Work Item on high power cab-radio [21]. This is in accordance with the recommendation in the report [6].

Observations from ETSI specification:

Compared with the 3GPP specifications [9] for LTE and [10] for NR, a new ETSI specification 103 807 [26] released in October 2021

- defines an maximum blocking level increased by 13 dB (from -43 dBm to -30 dBm),
- with a more realistic interfering LTE/NR FDD signal for the scenario instead of a CW interference signal as defined in 3GPP,
- at a lower level of the wanted uplink signal level ($P_{Refsense}$ + 1 dB instead of $P_{Refsense}$ + 6 dB), which is closer to the achievable cellular coverage without any interference.

Recommendations from ETSI specifications:

- For future MFCN sites and upgrades of base station equipment at existing sites, the enhanced selectivity specifications from ETSI should be taken as a basis.

Observations and recommendations from our Blocking Level Analysis:

- Additional interference mitigation like antenna discrimination and/or filtering is required for the uplink frequency band 1 at 1920-1940 MHz even for a distance separation between FRMCS and MFCN base stations of more than 3 km. Note that this and the following observations are valid for any similar MFCN uplink in European countries in frequency band 1 at 1920-1940 MHz that is near FRMCS downlink in band n101.
- Co-located installations of uncoordinated 5G TDD and 4G/5G FDD Base Stations would result in strong interference especially in the MFCN uplink frequency band 1 at 1920-1940 MHz, both with back-to-back installations of the FRMCS and MFCN antennas with vertical separation of the antennas, and should be avoided.
- The examples for rotating the MFCN antenna sectors indicate, that some horizontal discrimination can also be achieved for even the worst sector at each MFCN site, if the sectors can be conveniently oriented, e.g. by 60°.
- The above observation (that co-located installations of uncoordinated 5G TDD and 4G/5G FDD Base Stations would result in interference especially in the MFCN UL frequency band 1 at 1920-1940 MHz and should be avoided), is in-line with the statement from 3GPP in [22]: "*For the derivation of the BS RF requirements it was assumed that the RMR and MFCN base stations are not co-located, and no coordination is necessary for RMR BS deployment.*"

- No additional antenna discrimination and/or RF filtering is required for other uplink bands than the main frequency band 1 / n1 evaluated in this study
  - for a separation distance of 370 m with an NLoS propagation model for base stations and
  - for a separation distance of 500 m with a LoS propagation model as used in the CEPT reports.

Conclusion#1: Interference direction of FRMCS and MFCN networks

Interference of MFCN DL of 3GPP bands 3 and n3 on future FRMCS UL is less harmful due to a difference in the allowed interference level of 28 dB (which is equivalent to a distance factor of 25 under LoS conditions) between the allowed interference levels of -43 dBm and -15 dBm.

Conclusion#2: Interference by FRMCS UEs

Interference of FRMCS UE on MFCN UL is still harmful, even, when UE EIRP (+33 dBm) is 32 dB lower than from gNB (+65 dBm), because UE might pass-by with much smaller distance at MFCN gNBs. However, the interference would be limited in time for the presence of the train, but potentially higher in time share due to the asymmetric UL:DL ratio 3:1 of planned FRMCS.

Minimum LoS distance is 450 m, (assuming both UE and MFCN eNB antenna main lobes and full UE transmit power) to keep the -43 dBm blocking levels.

Conclusion#3: Interference by FRMCS gNBs

Interference of the FRMCS gNB on the MFCN UL is the major problem when FRMCS will be deployed as described in the CEPT reports.

The strong FRMCS carrier counts as interfering signal. To keep the interference level of -43 dBm, a theoretical distance of several km would have to be kept under LoS conditions (assuming the Tx and Rx antenna main lobes). For example, with 65 dBm of EIRP from an FRMCs base station, a MFCN BS even 3 km away might needs 12.3 dB of additional interference mitigation through antenna discrimination and/or filtering.

Conclusion#4: Lab measurements with real equipment

The effect of interference might depend on the specific location of the interfering signal at a frequency location from 10 to 20 MHz apart of the uplink carrier, and the real achieved maximum blocking power levels of the equipment might deviate/exceed 3GPP specifications.

Therefore, measurements with the existing MFCN base station equipment are recommended, e.g. with a micro core network and with an unsynchronized interfering 5G gNB with the specific TDD configuration of FRMCS (TDD, UL to DL ratio 3:1).

As a result, the interference effects like power levels and influence of the frequency locations are better understood and several interference mitigation techniques despite of the antenna discrimination can be optimized in regard of effort and costs, like additional filtering, and/or the 3GPP defined feature *Additional-Maximum Power Reduction* (A-MPR) for reduced power of Resource Blocks in the Uplink transmissions nearer to the MFCN spectrum.

These measurements could be done with a conducted setup in the lab to have well defined power levels of wanted uplink and interfering signals. An additional interfering 5G base station can be implemented e.g. with a Software Defined Radio gNB, e.g. from Amarisoft [15].

Conclusion#5: Benefit of additional Filters

Introducing additional notch filters to suppress the FRMCS carrier at 1900 to 1910 MHz will decrease the interference levels significantly (better than other interference mitigation methods) and would work with any multi-band base station.

As an example, considering the worst case in Figure 24, i.e., with FRMCS BS transmitting at +65 dBm EIRP under the EPM-73 path loss model, note that with antenna discrimination alone (~ 10 dB), the required spatial separation between MFCN and FRMCS sites is above 3.6 km.

By introducing a notch filter that is adding 40 dB more attenuation, the required spatial separation becomes only 56 meters.

Using such a filter would of course be with the penalty of

- **passband losses**, which is max 0.75 dB for the exemplarily filter, reducing the effective DL carrier power as well as the uplink sensitivity.
- **costs** - these notch filters start with several hundreds of € per piece, excl. installation costs on site.

2 Table of Content

3 Acronyms

3GPP	3rd Generation Partnership Project
5G	5th Generation
AAS	Active Antenna System
ACLR	Adjacent Channel Leakage Ratio
AS	Access Stratum
BEM	Block Edge Mask
BS	Base Station
CEPT	European Conference of Postal and Telecommunications Administrations
CW	Continuous Wave
DL	Downlink
ECC	Electronic Communications Committee
EIRP	Equivalent Isotropic Transmit Power
EUTRA	Evolved Universal Terrestrial Radio Access
EVM	Error Vector Magnitude
FDD	Frequency Division Duplex
FRMCS	Future Railway Mobile Communication System
GSM-R	GSM Railway
IIP3	Input Intercept Point 3rd order
IIS	Institut für Integrierte Schaltungen
ITU	International Telecommunication Union
LRTC	Least Restrictive Technical Conditions
MCL	Minimum Coupling Loss
MCS	Modulation and Coding Scheme
MER	Modulation Error Ratio
MFCN	Mobile / Fixed Communication Networks
MIMO	Multiple Input Multiple Output
NF	Noise Figure
NR	New Radio
OTA	Over The Air
RAN	Radio Access Network
RB	Resource Block
RE	Resource Element
RF	Radio Frequency
RMR	Railway Mobile Radio (term in 3GPP for FRMCS)
RRU	Remote Radio Unit
RX	Receiver
SCS	Sub Carrier Spacing
SNR	Signal to Noise Radio
TDD	Time Division Duplex
TR	Technical Report
TS	Technical Specification
TX	Transmitter
UE	User Equipment
UL	Uplink

4 Applicable and Referenced Documents

[1] B. Holfeld, "5GRAIL Nets4* Workshop International Workshop on Communication Technologies for Vehicles", 16/17 November 2021

[2] CEPT Report 39, "Report from CEPT to the European Commission in response to the Mandate to develop least restrictive technical conditions for 2 GHz bands", 2010-06

[3] CEPT Report 74, "Report from CEPT to the European Commission in response to the Mandate on spectrum for the future railway mobile communications system Report A: Spectrum needs and feasibility (tasks 1 to 4)", 2020-07

[4] ECC Report 294, "Assessment of the spectrum needs for future railway communications", 2019-02

[5] ECC Report 314, "Co-existence between Future Railway Mobile Communication System (FRMCS) in the frequency range 1900-1920 MHz and other applications in adjacent bands", 2020-05

[6] ECC Report 318, "Compatibility between RMR and MFCN in the 900 MHz range, the 1900-1920 MHz band and the 2290-2300 MHz band", 2020-07

[7] ECC Decision (20)02: "Harmonised use of the paired frequency bands 874.4-880.0 MHz and 919.4-925.0 MHz and of the unpaired frequency band 1900-1910 MHz for Railway Mobile Radio (RMR)"

[8] European Commission implementing Decision (EU) 2021/1730 on the harmonised use of the paired frequency bands 874,4-880,0 MHz and 919,4-925,0 MHz and of the unpaired frequency band 1 900-1 910 MHz for Railway Mobile Radio, 28 September 2021

[9] 3GPP TS 36.101, "LTE; Evolved Universal Terrestrial Radio Access (E-UTRA); User Equipment (UE) radio transmission and reception", v17.5.0 (2022-05)

[10] 3GPP TS 38.101-1, "User Equipment (UE) radio transmission and reception; Part 1: Range 1 Standalone (Release 17)", v17.5.0, 2022-03)

[11] 3GPP TS 36.104, "LTE; Evolved Universal Terrestrial Radio Access (E-UTRA); Base Station (BS) radio transmission and reception", v17.5.0 (2022-04)

[12] 3GPP TS 37.104, "Digital cellular telecommunications system (Phase 2+) (GSM); Universal Mobile Telecommunications System (UMTS); LTE; 5G; NR, E-UTRA, UTRA and GSM/EDGE; Multi-Standard Radio (MSR) Base Station (BS) radio transmission and reception", v17.5.0 (2022-04)

[13] 3GPP TS 38.104, "5G NR; Base Station (BS) radio transmission and reception (3GPP TS 38.104 version 17.5.0 Release 17)", v17.5.0 (2022-04)

[14] Wainwright Instruments RF notch filters, https://www.wainwright-filters.com/standard-filters/band-reject-notch-filters

[15] Amarisoft Software Defined Radio base station and core network, https://www.amarisoft.com/products/test-measurements/amari-lte-callbox/

[16] European Cooperation in the Field of Scientific and Technical Research, EURO-COST 231, "Urban Transmission Loss Models for Mobile Radio in the 900 and 1800 MHz Bands", COST 231 TD (91) 73. Rev 2, The Hague, September 1991.

[17] 3GPP RP-221768, Work Item Description, "Introduction of 900MHz NR band for Europe for Rail Mobile Radio (RMR)", Union Inter. Chemins de Fer (UIC), approved 2022-06

[18] 3GPP RP-211496, Work Item Description, "Introduction of 1900MHz NR band for Europe for Rail Mobile Radio (RMR)", Union Inter. Chemins de Fer (UIC), Ericsson, approved 2021-06

[19] 3GPP RP-221049 "LS to 3GPP RAN WG4 on the interferer signal definition for the RMR900 BS Rx blocking requirement", ETSI TC RT, noted 2022-06

[20] 3GPP RP-221816 Status Report, "Introduction of 900MHz NR band for Europe for Rail Mobile Radio (RMR)", Union Inter. Chemins de Fer (UIC), noted 2022-06

[21] 3GPP RP-221878 Work Item Description, "CAB-radio - High Power UE support for band n100 and n101 for Rail Mobile Radio (RMR) in Europe", UIC, Nokia, Ericsson, approved 2022-06

[22] 3GPP RP-221215 TR 38.852 v1.0.0 (2022-05) for approval, "Introduction of 1900MHz NR band for Europe for Rail Mobile Radio (RMR) (Release 17)", Union Inter. Chemins de Fer (UIC), approved 2022-06

[23] 3GPP RP-220376, "RAN4 CRs for Open REL-17 NR or NR+LTE WIs - Batch 33" (Change Request Package to introduce band 101 in TS 36, 37 and 38 series), approved 2022-03

[24] An Empirical Propagation Model (EPM-73), M. N. Lustgarten and J. A. Madison, IEEE: "Transactions on Electromagnetic Compatibility, Vol. EMC-19", NO. 3, August 1977

[25] European Communications Office (ECO), "ECO Report 03, The Licensing of "Mobile Bands" in CEPT, 2022-05-04

[26] ETSI Technical Specification 103 807, "Mobile Standards Group (MSG); IMT Cellular Networks Base Stations (BS) Additional Regulatory Requirements", v1.1.1 (2021-10)

[27] F. Gunnarsson et al., "Downtilted Base Station Antennas - A Simulation Model Proposal and Impact on HSPA and LTE Performance," 2008 IEEE 68th Vehicular Technology Conference, Calgary, AB, Canada, 2008, pp. 1-5

5 Goal of the Study

Goal of this study is to analyse the coexistence of an existing 4G/5G MFCN and the planned 4G/5G network for trains, called Future Railway Mobile Communication System (FRMCS). Since a significant share of the MFCN sites is located in the vicinity of the railroads of the Rail operator or their buildings, the potential interference caused by the new FRMCS system plays a significant role. Likewise, a potential interference of the safety-related FRMCS by the existing MFCN network is relevant. It shall be analysed, under which conditions the coexistence of both networks with the small frequency separation is possible, with minimum interference effects.

Focus of the study is in relation to the following statements from ECC reports 318 [6] and CEPT report 74 [3], which are unfavourable for the existing MFCN network in band 1:

- *"FRMCS BS are expected to operate in 1900-1910 MHz, which is 10 MHz away from the lower edge of the 3GPP UL band #1. Thus, FRMCS BS may interfere ECS BS receiving above 1920 MHz." [CEPT Report 74]*
- *„The BEM for the transmitter emissions would not avoid all interference that might arise in certain deployment scenarios, including for some configurations at shared base station sites or between nearby base station sites. In these situations, mobile network operators and RMR operators of both systems may have to coordinate, and the use of additional interference mitigation techniques might be considered." [ECC 318]*
- *"Additional mitigation techniques need to be implemented on a case-by-case basis, such as adjustments of antenna directivity, azimuth, tilt, or improve the selectivity of the MFCN BS in the vicinity of the railway tracks"* und *"In order to ensure that the MFCN operators have enough time to adapt the relevant radio sites, the RMR operator is required to perform an early notification procedure in advance of the rollout of a new FRMCS BS." [ECC 318]*

The last statement seems to be at least questionable, because MFCNs already exist and an FRMCS network will be deployed only in the future, considering interference minimization already during the planning phase of the FRMCS network.

Despite, a retrofitting in existing sites of an MFCN might be difficult and the introduction of FRMCS might complicate to fulfil the coverage obligations for mobile network operators by some of the national regulators.

Therefore, it is important in this study to analyse the scenarios with the smallest interference between the two systems and to identify the conditions for a coexistence of the MFCN and FRMCS.

- Rural, urban and suburban environment classes are considered
- For our analysis, a distance range between FRMCS base stations and MFCN base stations is assumed, including the co-located scenario, where MFCN and FRMCS base stations are on the same mast.

Parameters for the analysis are:

- Out of Band / Out of Carrier emissions
- Blocking caused by too high signal levels, e.g., from DL carriers signals of a base station on the Uplink of another base station.

We will investigate the following within the study:

* Interference of the FRMCS system on the MFCN NR/LTE network at 2100 MHz (band 1, n1)
* Interference of the FRMCS system in the MFCN NR/LTE network at 1800 MHz (band 3, n3)
* Interference of the MFCN NR/LTE network at 1800 and 2100 MHz in the FRMCS network at 1900 MHz (band n101)

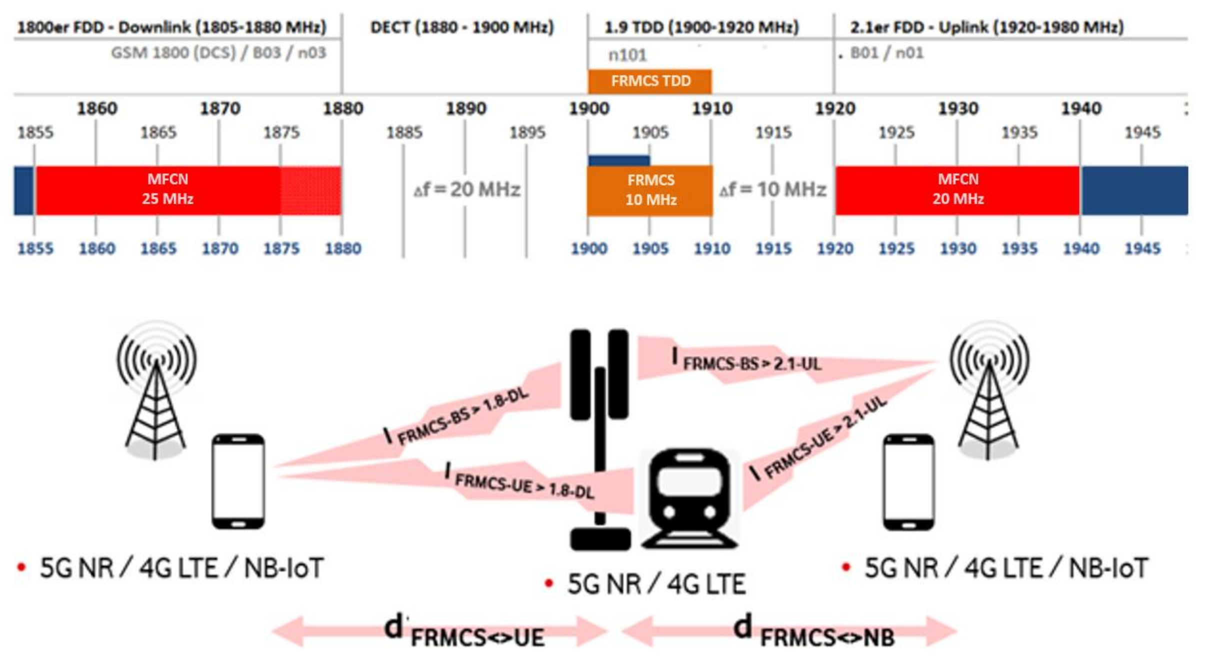

Figure 1: Scenario of interest; the new 5G frequency band n101will be used for the future FRMCS deployments [© Vodafone].

6 Scenario with 4G and 5G Deployments

6.1 FRMCS Deployment Parameters from CEPT Reports

The Future Railway Mobile Communication System (FRMCS) will replace in the long term the existing deployed GSM-R system, covering approx. 130 000 km of railway tracks in Europe. The end of GSM-R operations is estimated to be around 2035. Start of deployment of the new FRMCS is approximately planned from end 2025 [1]. According to CEPT reports, the sites from GSM-R will be mostly re-used for the deployments of FRMCS.

In ECC report 318 [6], for example, the GSM-R network by DB Netz AG is described, which is operational since 2004. Key figures are stated as follows in [6]:

- *"DB Netz AG is using 2 x 7 MHz in the 873-880 MHz (uplink)/918-925 MHz (DL) band for the GSM-R radio network;*
- *The GSM-R deployment in Germany is designed to meet the EIRENE specifications [1];*
- *The GSM-R cell radius is in the range of a few hundred meters to several kilometres;*
- *GSM-R applications and services with dedicated antennas, no in train coverage for GSM-R;*
- *Current GSM-R radio BTS configurations typically use one or two GSM-R RF carriers per radio cell. In dense areas, up to 4 GSM-R RF carriers per radio cell are used today;*
- *Covered track length: ca. 29500 km;*
- *Dedicated GSM-R tunnel coverage, mainly in metropolitan areas and on high-speed lines with a total length of more than 500km[2];*
- *ca. 3900 GSM-R radio sites.*

[1] EIRENE SRS v16.0.0: "System Requirements Specification"

[2] https://fahrweg.dbnetze.com/fahrweg-en/customers/network_statement/infrastructure_register/principles-1394986

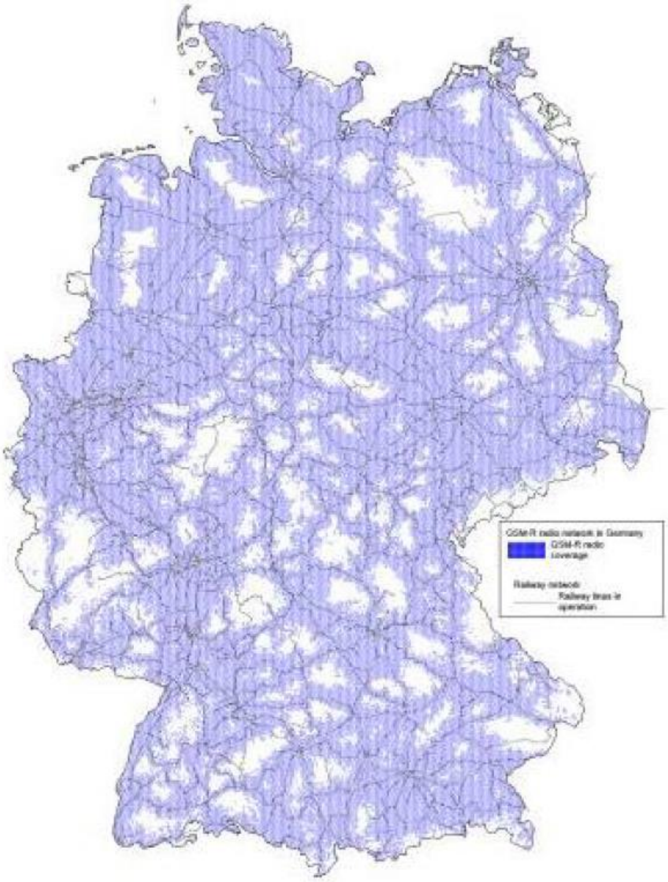

Figure 56: RMR (GSM-R) radio network in Germany

Figure 2: GSM-R network by DB Netz AG, picture from [6].

In October 2018, the actual GSM-R frequency assignment and authorisation process has successfully completed for

- *ca. 3900 GSM-R radio sites;*
- *ca. 4300 GSM-R radio cells;*
- *ca. 9800 GSM-R antenna data records (per antenna and frequency).*

Table 1: Deployment environment of current GSM-R radio sites within 600 m buffer of RMR [6].

	RMR	MFCN (within 600m of RMR)
∑ Antenna data records	ca. 9800	ca. 20.000
Radio technologie	GSM-R	GSM900, LTE900
Dense enviroment (e.g. urban)	Ca. 5100	Ca. 17.000
Agriculture enviroment (rural)	Ca. 2800	Ca. 1700
Forest (rural)	Ca. 1900	Ca. 1500

This table shows significant differences between the deployed radio networks studied. In dense environments (e.g. urban, sub-urban, industrial…) 85% of MFCN antennas within the 600 m buffer of RMR sites are located. Ca. 45% of the RMR antennas can be found in rural environments. It can be noted that for comparing RMR and MFCN deployment environments, significantly differences become apparent".

Observations from ECC report 318 [6]:

- The sites from GSM-R will be mostly re-used for the future deployments of FRMCS.
- Approximately 3900 GSM-R radio sites are currently installed, with 4300 radio cells and 9800 antenna data records per antenna and frequency
- Approx. 45% of RMR antennas are located in rural areas and 55% in dense urban environment.

3GPP currently introduces two new frequency bands for FRMCS in 900 and 1900 MHz respectively, named band n100 and n101. Further details and references are described in chapter 7.2.

Use cases, spectrum needs and deployment parameters are mainly summarized in several CEPT and ECC reports, which will be summarized in the following.

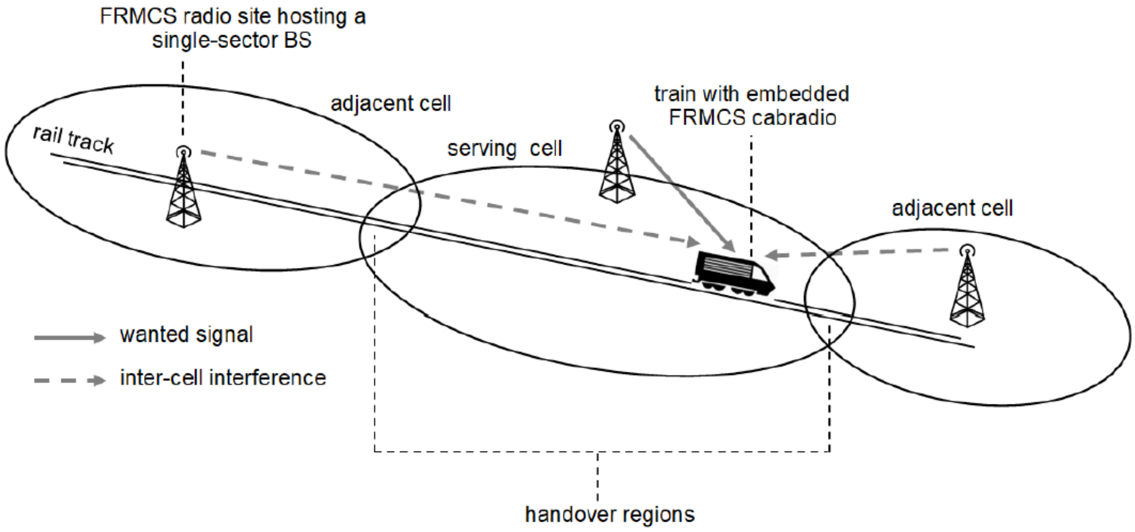

Figure 3: General FRMCS architecture from ECC report 314 [5].

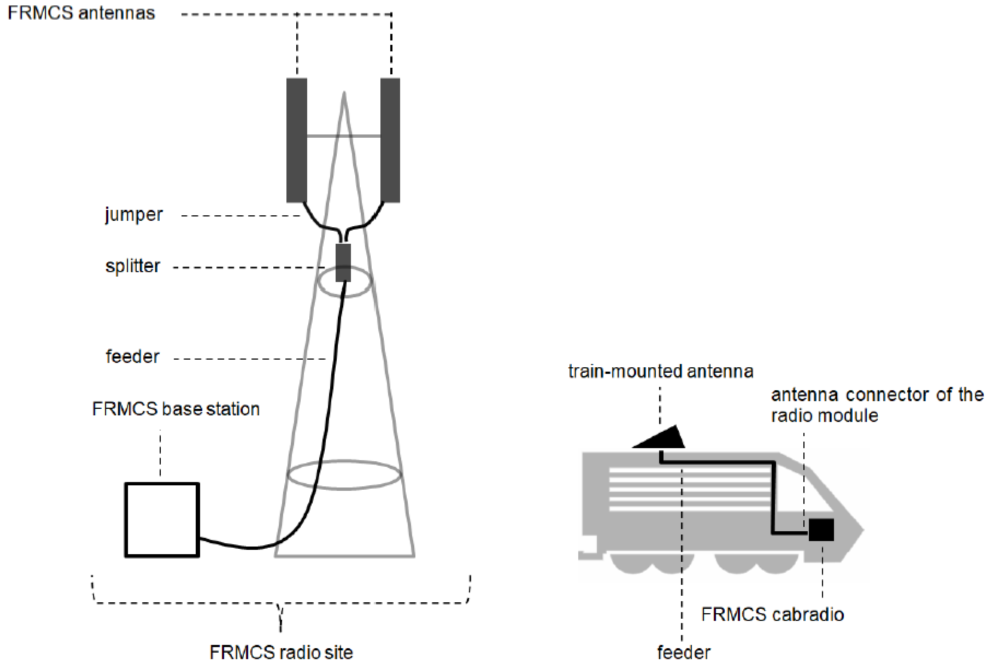

Figure 4: FRMCS Base stations and on-board UEs from ECC report 314 [5].

The figure below summarizes all relevant documentation from CEPT on use cases, spectrum needs, deployment parameters and interference studies. A detailed analysis of the interference studies is provided in chapter 7.1.

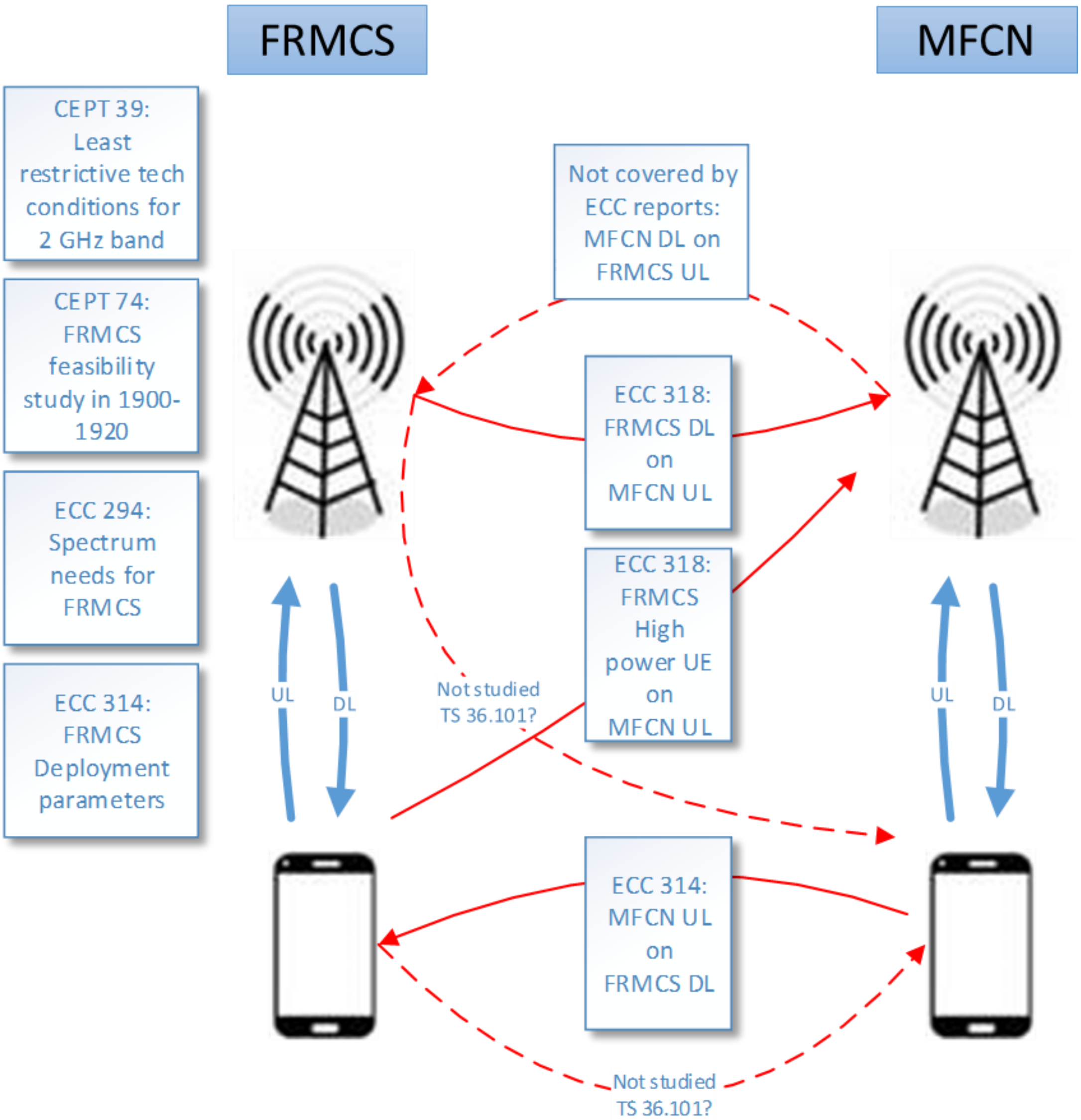

Figure 5: Overview on system definitions and interference studies for FRMCS from CEPT and ECC reports

Table 2: General parameters for FRMCS from ECC report 314 [5]

Parameter	Value	Our Notes
Operating Band	E-UTRA TDD operating band 33	This is the LTE frequency band definition; for 5G NR, this is the new band n101 as specified in TS 38.104 [13].
Centre frequency	1905 MHz	
Channel bandwidth	10 MHz	
TDD configuration	Frame configuration 0 Special subframe configuration 6	*Frame structure for TDD configuration 0 is |D|S|U|U|U|D|S|U|U|U|, where D denotes a DL, U an uplink, and S a special subframe.* This means a different configuration to public 5G networks with an UL – DL ratio of 3:1, so approx. 20 % of time the MFCN UL resources are affected
Maximum number of resource blocks	50	This is the nominal number of RBs for LTE; for 5G NR, 52 RBs are specified in TS 38.104 [13]
Occupied bandwidth	9.0 MHz	Active RF bandwidth with 50 * 12 * 15 kHz (SCS); for 5G NR, it would be 52 * 12 * 15 kHz = 9.36 MHz, or 24 * 12 * 30 kHz = 8.64 MHz.
FRMCS radio sites	Same sites as for GSM-R coverage	Detailed information about GSM-R sites is given in ECC report 318 Annex 5 [6].
Frequency reuse scheme	See Figure 6	

Table 3: Parameters for FRMCS Base stations from ECC report 314 [5]

Parameter	Value	Our Notes
Maximum output power per antenna connector	+46 dBm	This is a power level for macro base stations; the interference evaluations in the CEPT reports consider lower power levels as well.
Unwanted emissions	Given in 3GPP TS 36.104, table 6.6.3.2.1-6 (OBUE for Category B Option 1 BS) and table 6.6.4.2.1-1 (spurious emissions)	
Feeder loss	4 dB	
Antenna height, azimuth and tilt	Two antennas per FRMCS site (see Figure 4) Same height, azimuth and tilt as already	

	deployed antennas for GSM-R coverage	
Antenna type	Passive sectoral panel antennas	
Transmit diversity gain	3 dB	
Antenna pattern	Recommendation ITU-R F.1336-5 [19], section 3.1.1 or 3.1.2 with improved side-lobe efficiency: kk_{pp}=0.7; kk_{aa}=0.7; kk_{h}=0.7; kk_{vv}=0.3	
Antenna pattern parameters	Peak gain = 18 dBi Horizontal Half-Power Beamwidth (HPBW) = 65° Vertical HPBW = 8.5°	

Table 4: Parameters for FRMCS UEs from ECC report 314 [5]

Parameter	Value	Our Notes
Maximum output power per antenna connector	+31 dBm	Number of antenna connectors is not explicitly stated in ECC report. In the same report, a single port UE antenna is referenced, but this would not comply with 5G specifications, where only for new RedCap UEs from Rel-17, the number of antenna ports can be one.
Unwanted emissions	Given by 3GPP TS 36.101, table 6.6.2.1.1-1 (SEM) and table 6.6.3.1-2 (spurious emissions)	
Noise figure	5 dB	
Noise floor per Resource Block (RB)	-116.4 dBm	
Third order intermodulation intercept point (IIP3)	-20.6 dBm	
Hardware losses	3 dB	High loss due to required cabling inside a cab.
Antenna pattern	Huber+Suhner 1399.99.0121	Gain in horizontal plane is 0 … +6 dBi at 25° elevation, so rather omni-directional. In contrast, the assumed antenna gain in ECC report 318 is 5 dBi.
Antenna height above railway track	4 m	UE antenna on the cab roof.
Power control	enabled	

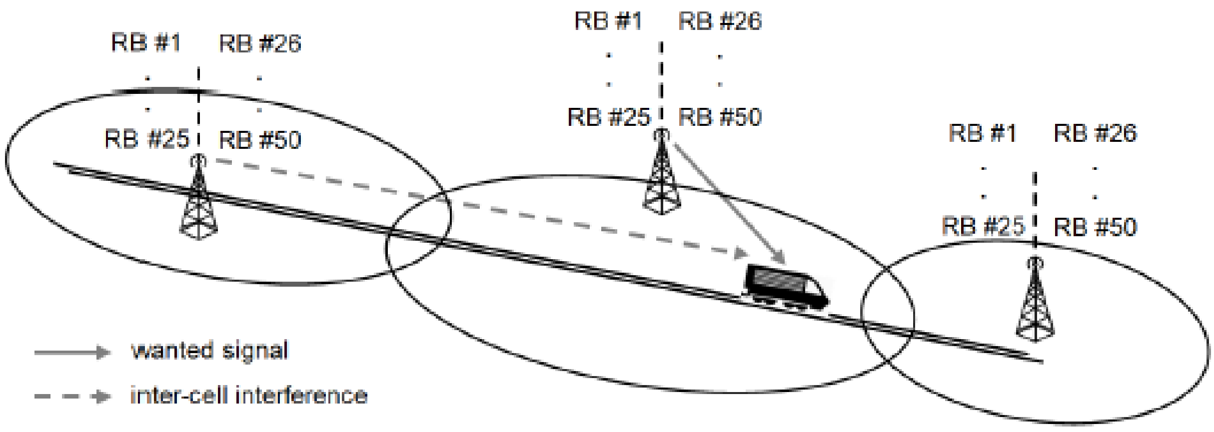

Figure 4: Assumed frequency reuse scheme and Inter-Cell Interference

Figure 6: Resource usage of FRMCS: half of spectrum is allocated to the 2 sectors, from ECC report 318 [6]

7 Review of Literature on Interference

7.1 CEPT Documents

This section summarizes relevant points from the review of the CEPT documents ECC 314 [5] and ECC 318 [6]. Note that only parts of the reports, specifically, concerning the interference between FRMCS in 1900 – 1910 MHz band and the MFCN UL operating above 1920 MHz are discussed here.

7.1.1 Impact of MFCN UL on FRMCS DL as per ECC Report 314

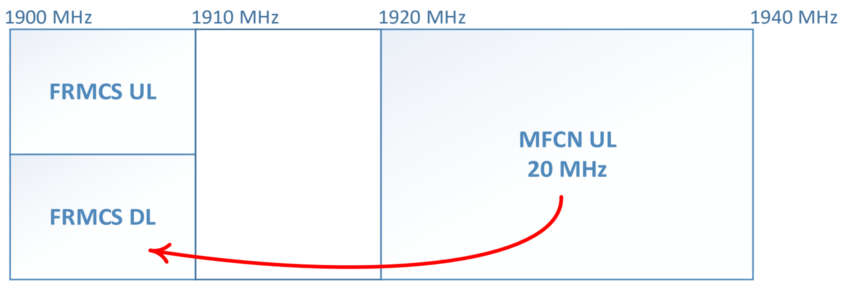

Figure 7: Relevant interference scenarios addressed in ECC 314 [5]: the impact of MFCN UE transmissions on the FRMCS UE reception is investigated.

As indicated in Figure 5 and Figure 7, the CEPT report ECC 314 [5] studied the impact of MFCN UE transmissions from the 1920–1940 MHz band on the FRMCS UE (cab-radio) reception at the 1900–1910 MHz band. Specifically, among the three MFCN systems that may be deployed in 1920–1980 MHz MFCN band, the 20 MHz channel centred at 1930 MHz is considered as the worst case assumption for the co-existence with FRMCS.

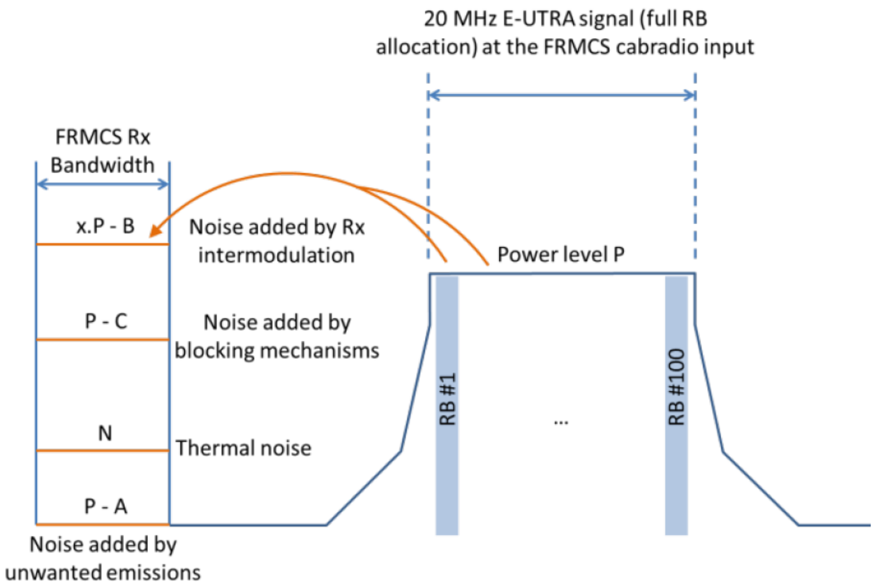

Figure 16: Interference of FRMCS cab-radios through unwanted emissions, blocking mechanisms and receiver intermodulation

Figure 8: Depiction of main interference mechanisms noted in ECC 314 [5] showing how MFCN UL transmissions may affect FRMCS reception.

It is found that the main mechanism by which MFCN UEs interfere with FRMCS cab-radios is the unwanted emissions falling into the FRMCS channel (see Figure 8), neither the blocking nor the intermodulation. In summary of the simulation-based evaluation of unwanted emissions, it is concluded that the FRMCS cab-radios would not face DL throughput degradation, even when the train is passing by a terminal in close proximity to the rail track, which is the configuration resulting in the maximum desensitization.

Regarding the coexistence with MFCN and FRMCS systems, while the ECC 314 report addresses only the above case of FRMCS being the interfered-with system, the more relevant case of FRMCS being the interferer on MFCN is addressed in the report ECC 318 [6], which is reviewed in the next subsection. Before that, regarding another scenario addressed in ECC 314, i.e., the coexistence of FRMCS with the DECT (Digital Enhanced Cordless Telecommunications) system in 1880-1900 MHz, a few points on FRMCS being the interferer are worth noting [5]:

> *"**Unwanted emissions are not the only mechanism by which FRMCS base stations and on-board equipment can interfere with other systems in adjacent bands: blocking and intermodulation also need to be considered**. These two effects depend fundamentally on the structure of the interfering signal in terms of Power Spectral Density (PSD). As seen in section 2.2.2, a 10 MHz NR carrier used in FRMCS would most likely be configured with 15 kHz SCS, and therefore comprise 624 regularly*

spaced subcarriers (There are 52 Resource Blocks (RB) in a 10 MHz carrier when SCS = 15 kHz, see 3GPP TS 38.101, table 5.3.2.-1, and each RB comprises 12 subcarriers, independently of the SCS). The signal structure is almost the same as for a 10 MHz LTE carrier, whose occupied bandwidth is slightly smaller because it has only 50 RBs (see 3GPP TS 36.101, table 5.6-1), which results in 600 subcarriers."

Also worth noting from [5] are the following requirements for the FRMCS receivers (cab-radio and BS), specified considering the importance of blocking and intermodulation.

Table 1: Requirements on FRMCS cab-radio receiver characteristics

Parameter	Value
Level of the wanted signal	sensitivity + 3 dB
Maximum 5 MHz LTE interfering signal in 1805-1880 MHz	-13 dBm
Maximum 5 MHz LTE interfering signal in 1920-1980 MHz	-39 dBm
Note 1: The antenna connector of the radio module is the reference point. Note 2: These requirements cover both blocking and third-order intermodulation.	

Figure 9: Requirements for FRMCS UEs specified in [5] considering blocking and intermodulation.

Table 2: Requirements on FRMCS BS receiver characteristics

Parameter	Value
Level of the wanted signal	sensitivity + 3 dB
Maximum 5 MHz LTE interfering signal in 1805-1880 MHz	-20 dBm
The antenna connector of the BS receiver is the reference point. These requirements cover both blocking and third-order intermodulation.	

Figure 10: Requirements for FRMCS BS specified in [5] considering blocking and intermodulation.

7.1.2 Impact of FRMCS DL/UL on MFCN UL as per ECC Report 318

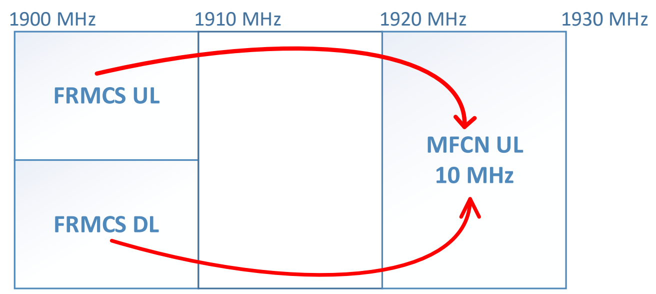

Figure 11: Relevant interference scenarios addressed in ECC 318 [6]: the impact of FRMCS BS and UE transmissions on the MFCN BS reception is investigated.

Out of the several cases studied in the CEPT report ECC 318 [6], the relevant ones of our interest are reviewed in this section:

Compatibility of FRMCS in part of 1900-1920 MHz with MFCN;

- *Impact of FRMCS BS on MFCN BS receiving above 1920 MHz;*
- *Impact of FRMCS high-power UE on MFCN BS receiving above 1920 MHz.*

As indicated in Figure 5 and Figure 11, [6] evaluated the impact of FRMCS BS and high-power UE (cab-radio) transmissions from the 1900 –1910 MHz band on the MFCN UL reception in the 1920–1930 MHz band. More specifically, the Least Restrictive Technical Conditions (LRTC) in the form of Block Edge Mask (BEM) for the FRMCS transmission are derived so as to minimize the interference experienced by the MFCN UL, however, **focusing on the unwanted emissions (neither blocking, nor intermodulation)**.

Observations from CEPT Reports:

Informative key points from the executive summary in [6] are given below to note the approach and intention of the CEPT evaluation:

- *Only non-AAS FRMCS and non-AAS MFCN systems have been considered. Additional studies should be performed in case AAS systems are considered for FRMCS in the 1900-1910 MHz band. The protection of MFCN 5G NR with AAS BS above 1920 MHz was not studied in this Report. Further analysis of the interference impact of FRMCS on MFCN AAS systems may be required.*
- *As described in CEPT Report 19, the BEM is developed on the basis that detailed coordination and cooperation agreements would not be required to be in place prior to network deployment.* ***The BEM for the transmitter emissions would not avoid all interference that might arise in certain deployment scenarios, including for some configurations at shared base station sites or between nearby base station sites. In these situations, mobile network operators and RMR operators of both systems may have to coordinate, and the use of additional interference mitigation techniques might be considered.***

7.1.2.1 BEM (Block Edge Mask) Derivation Methodology

As indicated above, the least restrictive technical conditions (LRTC) derived for RMR BSs are in the form of a block-edge mask (BEM). The different components of a BEM are illustrated in the figure from [6] below.

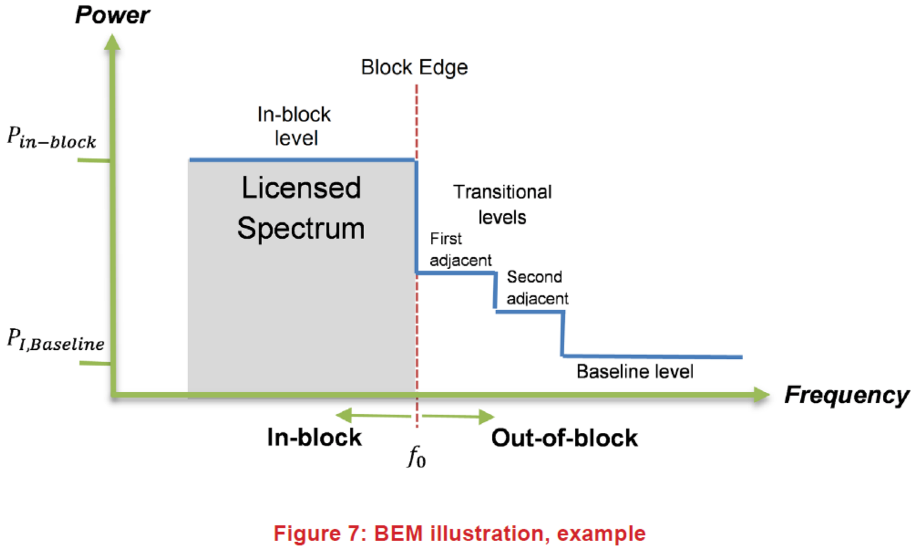

Figure 12: Figure from [6] showing the components of a block edge mask (BEM).

As described in [6],

> *'in order to derive a BEM for RMR BS, a reference minimum coupling loss (MCL) has to be defined. For this purpose, two MCL calculation approaches have been considered: one based on 100 m separation distance between BS and one based on statistics relying on existing GSM-R and MFCN deployment data in France, Germany and Sweden. The statistical approach appears to be of particular relevance when the two systems under study exhibit significant differences in their deployment patterns, notably as a result of different coverage targets.'*

The equation for MCL computation as presented in [6] for the 100 m separation assumption is as follows

$$MCL = PL_{(f,d)} - G_{Rail} - G_{MFCN} + D_{Rail} + D_{MFCN}$$

where:

- $PL_{(f,d)}$ is the path loss between the two base stations under consideration, operating frequency f with separation distance d
- D_{Rail} is the RMR antenna vertical discrimination
- D_{MFCN} is the MFCN antenna vertical discrimination
- G_{Rail} is the RMR antenna gain (including feeder and coupling losses)
- G_{MFCN} is the MFCN antenna again (including feeder loss). No horizontal discrimination is taken into account.

Although no horizontal antenna discrimination (see Figure 13) is considered for the results based on the 100 m separation assumption presented in [6], note that it might be significant and therefore considered in the statistical approach, where

- D_{Rail} is the RMR antenna discrimination (vertical and horizontal)
- D_{MFCN} is the MFCN antenna discrimination (vertical and horizontal).

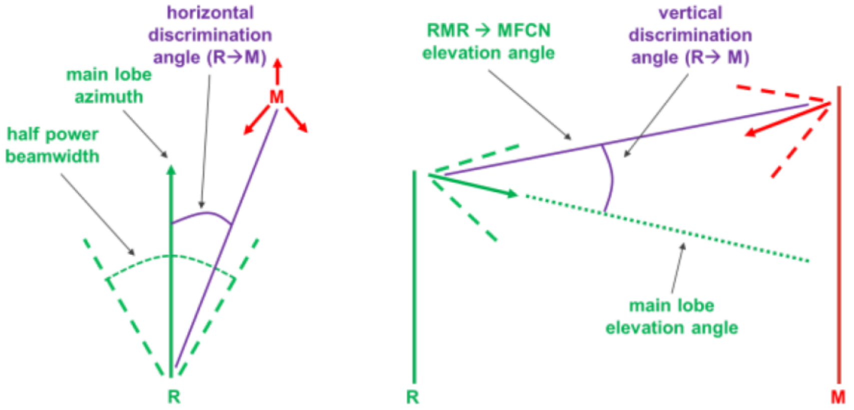

Figure 13: Horizontal and vertical antenna discriminations

Figure 13: Depiction of horizontal and vertical antenna discriminations between RMR (denoted by R) and MFCN (denoted by M) BSs from [6]. Note that the vertical antenna discrimination depends on the distance between the BS sites, height difference of the BS sites and the down-tilts, while the horizontal antenna discrimination only depends on the orientation of the sector beams.

While the free space path loss assumption is valid for 100 m separation, a BS-to-BS LoS propagation model is adopted for the statistical MCL calculation approach that would encounter distances beyond 100 m. As noted in [6]:

> *In this Report, an adaptation of the EPM-73 propagation model is used. EPM-73 is a LoS model applicable to "above rooftops" scenarios, to the frequency range 40 MHz to 10 GHz and for distances higher than 500 m. Below 100 m, the free space propagation model is considered. Between 100 m and 500 m, a linear slope between the two models is assumed.*

Necessary details of the EPM-73 model adaptation from [6] are note in the 'Annex – Propagation Models' in Section 10.

In general, higher antenna gains or lower antenna discriminations would decrease the MCL for a given distance, leading to higher interference. The resulting MCL value with the approach assuming 100 m BS-to-BS separation is 63 dB (for the 1900 MHz range of our interest) as listed in the following table shown in Figure 14, along with the considered parameters. Although horizontal discrimination is not accounted for in this MCL computation, an additional example considering horizontal discrimination is also provided in [6] where it is remarked that (see Section 3.3 in [6])

> *A discrimination of at least 8 dB from the GSM-R antenna can be obtained compared to the 100 m LoS.*

Table 12: MCL calculation

RMR range	919.4-925 MHz	1900-1910 MHz	Reference
f	920 MHz	1905 MHz	
d	100 m	100 m	
RMR-MFCN height difference	10 m	10 m	typical (Note 1)
PL	71.7 dB	78.0 dB	
G_{Rail}	13 dBi	14 dBi	
G_{MFCN}	12 dBi	15 dBi	
D_{Rail}	10 dB	11.5 dB	Recommendation ITU-R F.1336-5 [6] (Note 1)
D_{MFCN}	0.5 dB	2.5 dB	Recommendation ITU-R F.1336-5 [6] (Note 1)
MCL	57.2 dB	63 dB	(Note 1)
Note: If a 5 m height difference is assumed between RMR and MFCN antennas, D_{Rail} is 4 dB and D_{MFCN} is 0 dB leading to an MCL of 50.7 dB at 920 MHz and 53 dB at 1905 MHz. Depending on the antenna height difference, a lower MCL may be achieved further away than 100 m.			

Figure 14: Table in [6] showing the parameter values and the resulting MCL value for the 100 m BS-BS separation assumption . Recall that horizontal antenna discrimination is not included for this computation.

In the statistical approach [6], the distance d and the antenna parameters G_{Rail}, G_{MFCN}, D_{Rail}, and D_{MFCN} are randomized in simulation with the geometrical characteristics (locations of the emission/reception points, the spatial orientations and geometry of the antennas), antenna radiation pattern models and digital terrain model (via path loss). The resulting MCL value then is picked from the statistical result as follows [6]:

> *In order to select an MCL value, the following criterion has been selected: 7% of RMR sectors would have at least one MFCN neighbouring sector (from the operator the closest in frequency to the RMR lower band edge) with a coupling loss lower than that MCL value.* ***The threshold of 7% has been chosen as a compromise value between efficient use of RMR and protecting the incumbent.*** *Based on this criterion and on the figures above; the MCL value to be considered between RMR and MFCN BS in the 1900 MHz range is 73 dB.'*

Note that the MCL value is 10 dB more in comparison to the 63 dB from the 100 m based approach.

The LRTC derived based on the two different MCL values are listed in the tables from [6] reproduced in Figure 15 and Figure 16. The 100 m MCL calculation approach and the statistical approach, assuming a MFCN BS selectivity as per CEPT Report 39 [4], result in LRTC requiring in-block EIRP limit of 40.7 dBm/10 MHz and 50.7 dBm/10 MHz, respectively.

Table 18: 100 m based LRTC for wideband RMR BS, considering MFCN BS selectivity as per CEPT Report 39 [4]

RMR carrier	In-block e.i.r.p.	Out-of-band emissions	Baseline e.i.r.p. in 1920-1980 MHz
10 MHz LTE/NR in 1900-1910 MHz	40.7 dBm/(10 MHz)	as per TS 137 104 Table 6.6.2.1-1	-41 dBm/(5 MHz)

Figure 15: LRTC in [6] for RMR/FRMCS BSs with the minimum coupling loss computation based on assumption of 100 m seperation from the MFCN BS.

Table 19: LRTC for wideband RMR BS based on statistics, considering MFCN BS selectivity as per CEPT Report 39 [4]

RMR carrier	In-block e.i.r.p.	Out-of-band emissions	Baseline e.i.r.p.in 1920-1980 MHz
10 MHz LTE/NR in 1900-1910 MHz	50.7 dBm/(10 MHz)	as per TS 137 104 Table 6.6.2.1-1 [9]	-43 dBm/(5 MHz)

Figure 16: LRTC in [6] for RMR/FRMCS BSs with the minimum coupling loss computation based on the statistical approach.

Also considered is the operation of FRMCS with macro coverage and without in-block restriction subject to changes to MFCN BS selectivity. This requires an in-block EIRP of 65 dBm/10 MHz for FRMCS BS and leads to a BEM as specified in the table reproduced in Figure 17. It is noted that this might result in interference to several more MFCN BSs located near an FRMCS radio site.

Table 20: LRTC for wideband RMR BS, considering enhanced MFCN BS selectivity

RMR carrier	In-block e.i.r.p.	Out-of-band emissions	Baseline e.i.r.p. in 1920-1980 MHz
10 MHz LTE/NR in 1900-1910 MHz	65 dBm/(10 MHz)	as per TS 137 104 Table 6.6.2.1-1 [9]	-43 dBm/(5 MHz)
Note: In case an in-block e.i.r.p. higher than 65 dBm/10 MHz is desired by an administration, it is assumed that appropriate interference mitigation or coordination are put in place.			

Figure 17: LRTC in [6] for RMR/FRMCS BSs without in-block restriction; i.e., none of the MCL calculation methods is used to restrict the allowed power level, potentially interfering with many more MFCN BSs..

Observations from CEPT report:

Key points noted from the conclusions in [6]:

- With the current level of selectivity of MFCN base stations, the defined LRTC for FRMCS may result in interference to some MFCN base stations located near FRMCS BS sites. One way of addressing this interference is to coordinate FRMCS and MFCN deployments. However, this means that FRMCS operators may not be able to use +65 dBm at certain locations. If 65 dBm EIRP for uncoordinated FRMCS base stations is desired, then many MFCN BSs may need to be adapted when an FRMCS BS is rolled out in their proximity to minimize interference from FRMCS.

- Additional mitigation techniques need to be implemented on a case-by-case basis, such as adjustments of antenna directivity, azimuth, tilt, or improve the selectivity of the MFCN BS in the vicinity of the railway tracks.
- In order to ensure that the MFCN operators have enough time to adapt the relevant radio sites, the RMR operator is required to perform an early notification procedure in advance of the rollout of a new FRMCS BS.
- In order to enable an in-block EIRP of +65 dBm/(10 MHz) for FRMCS BS, the MFCN BS selectivity would need to be 98.3 dB (assuming an MCL of 63 dB measured at the antenna connector), which is
  - 24.3 dB more selectivity compared that in the CEPT Report 39
  - **40.6 dB more selectivity in compared to that in the 3GPP specification TS 37 104.**
- In order to enable an in-block EIRP of +65 dBm/(10 MHz) for FRMCS BS, the MFCN BS selectivity would need to be 88.3 dB (assuming an MCL of 73 dB measured at the antenna connector), which is
  - 14.3 dB more selectivity compared that in the CEPT Report 39
  - **30.6 dB more selectivity in compared to that in the 3GPP TS 37 104.**
- The interference from FRMCS cab-radio of +31 dBm output power to MFCN uplink is acceptable according to CEPT reports when uplink power-control is implemented and activated.

7.1.2.2 Co-Location of FRMCS and MFCN Base Stations

In case of co-located sites with FRMCS and MFCN base stations (as depicted in Figure 19) strong interference from the FRMCS DL carrier in 1900 – 1910 MHz into the MFCN uplink spectrum at 1920 – 1940 MHz and - depending on the real decoupling of the installation - a smaller share of MFCN sites in the other MFCN uplink bands having 28 dB higher allowed blocking levels would be the consequence.

According to the ECC report 318, for an uncoordinated deployment without interference coordination and a minimum distance between FRMCS and MFCN,

- the Minimum Coupling Loss (MCL) for this deployment scenario is 63 dB (incl. antenna gains and decoupling degradations) and
- the minimum free space path loss is 78 dB.

It is obvious that realistic path losses and coupling losses in such a co-located deployment scenario would hardly keep these values as requested by the ECC report. For an estimate of coupling loss in collocated deployments, as an example, consider the normalized gain pattern model used in 3GPP simulation scenarios [27] as reproduced in Figure 18. Specifically, with absolute peak gains of $G_{Rail} = 14$ dBi and $G_{MFCN} = 15$ dBi as per Figure 14, let us assume the normalized gain pattern in Figure 18 for both MFCN and FRMCS base station antennas. Then the received interference power at the MCFN BS can be computed as $P_i = (\text{FRMCS EIRP} - G_{Rail}) - MCL = 65\ \text{dBm} - PL_{(f,d)} + 15\ \text{dBi} - (D_{Rail} + D_{MFCN})$, which would then depend on pathloss and discrimination possible in the collocated scenarios in Figure 19:

- In case of **horizontal separation of FRMCS and MFCN base station antennas**, due to the front-to-back ratio of the two involved cellular antennas by the two base stations, $D_{Rail} + D_{MFCN} = 60$ dB is possible as per the horizontal gain patten in Figure 18, but only in the case that they are **installed back-to-back**, which seems not to be possible due to the planned deployment with two antennas per FRMCS base station in opposite directions as shown in Figure 4. In any case, **the received interference level would be much higher than the allowed blocking level of -43 dBm.**

- In case of a **vertical separation of FRMCS and MFCN base station antennas** at different heights, the required decoupling to mitigate interference is not sufficient as well. The relevant effective antenna gains in +/-90° vertical directions would then be 14 dBi – 18 dB = -4 dBi. The free space loss at 5 m separation is 52 dB at 1910 MHz. The effective interfering power level in such a scenario is $P_i = 65\ \mathrm{dBm} -\ 52\ \mathrm{dB} + 15\ \mathrm{dBi} - (18 + 18)\ \mathrm{dB} =\ -8\ \mathrm{dBm}$. So **for this example, the signal level in the MFCN uplink is approximately 35 dB above the allowed blocking level (-43 dBm) at a frequency separation of 10 MHz.**

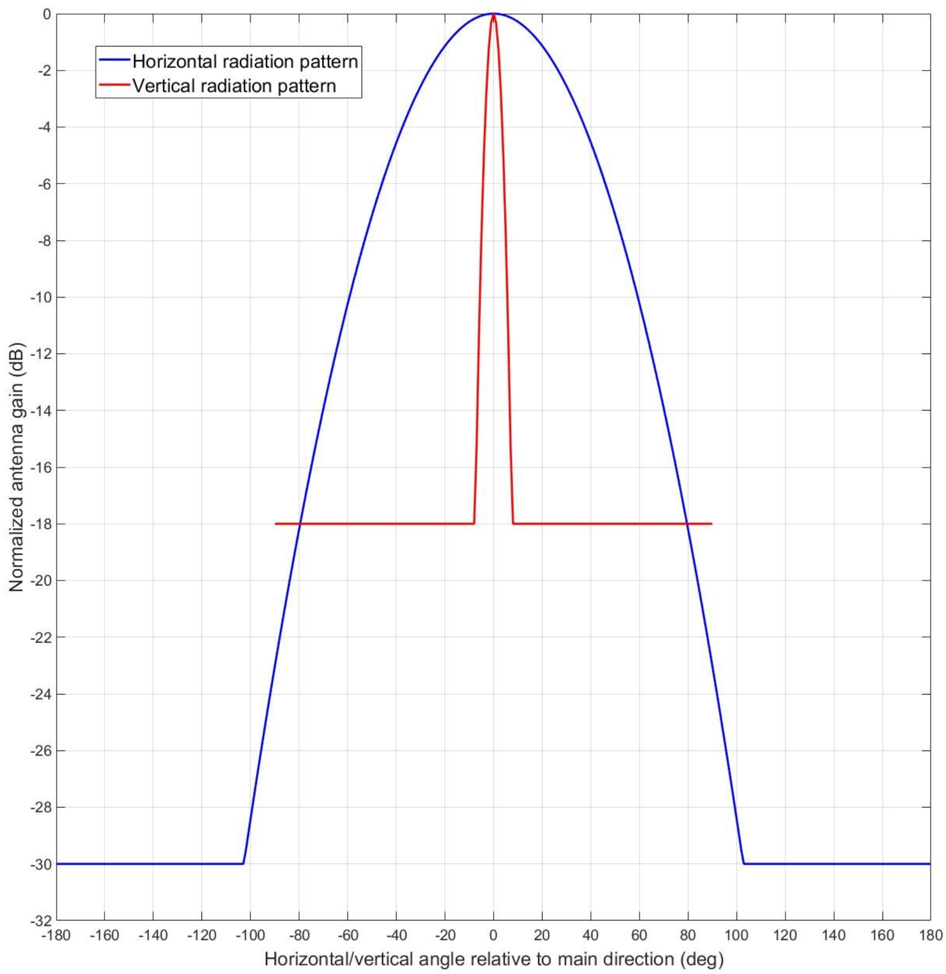

Figure 18: Exemplary antenna pattern as per the 3GPP simulation model proposed in [27].

As a remark, the four German 5G-TDD systems in band n78 at 3.4 to 3.7 GHz are coordinated both in time and in the TDD pattern, to avoid the direct DL-to-UL interference between two cellular networks. According to the 3GPP specifications, the allowed blocking levels for such a deployment with consecutive frequency allocations for the operators are exactly the same as in the deployment case of 10 MHz frequency separation between FRMCS and MFCN Base Stations.

Observations from CEPT reports:

Co-located FRMCS and MFCN sites would lead to strong interference especially in the UL of band 1 at 1920 to 1940 MHz, both with back-to-back installations of the FRMCS and MFCN antennas and with vertical separation of the antennas.

Recommendation from CEPT reports:

The recommendation is, that co-located installations of 5G TDD and 4G/5G FDD Base Stations would result in interference especially in the MFCN UL frequency band 1 at 1920-1940 MHz and should be avoided. This is in-line with the statement from 3GPP in [22] "*For the derivation of the BS RF requirements it was assumed that the RMR and MFCN base stations are not co-located, and no coordination is necessary for RMR BS deployment*."

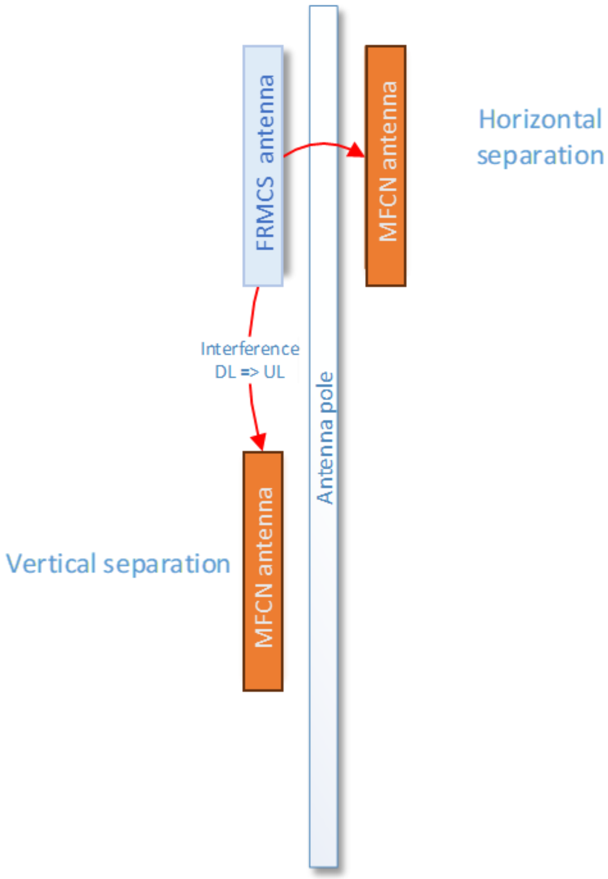

Figure 19: Interference in uncoordinated deployments with co-located 5G TDD and 4G/5G FDD systems. Neither vertical nor horizontal separation provide sufficient attenuation of the FRMCS DL carrier.

7.2 3GPP Specifications

Beside of the Radio Access Network (RAN) transmission waveform and protocol for the Access Stratum (AS), 3GPP specifies a comprehensive set of performance and conformance testing specifications for the RAN. There are different specification series available, e.g., TS 36.xyz series for 4G LTE, TS 38.xyz for 5G NR and TS 37.xyz for interoperability of 4G and 5G.

Relevant specification documents from 3GPP for this RF coexistence analysis are the following ones:

User Equipment (UE):

- TS 36.101 (LTE incl. NB-IoT) [9]
- TS 38.101-1 (NR, FR1) [10]

These 3GPP specification documents include the RF characteristics and performance specifications like:

- Operating bands
- Carrier bandwidth
- Transmitter (Uplink):
  - Transmit power levels
  - Spectrum emission masks,
- Receiver (DL):
  - Sensitivity
  - Demodulation performance for different reference propagation channels and Modulation and Coding schemes (MCS)
  - Maximum blocking power levels for different frequency separations between interfering and wanted uplink band

Base Station (LTE eNB, 5G gNB):

- TS 36.104 (LTE eNB incl. NB-IoT) [11]
- TS 37.104 [12]
- TS 38.104 (5G gNB) [13]

Similar to the UE specification documents, these specification for eNB/gNB include a comprehensive set of RF characteristics and performance specifications like:

- Operating bands
- Carrier bandwidth
- Transmitter (DL):
  - Transmit power levels
  - Spectrum emission masks, out-of-band emissions,
  - Modulation Error Ratio (MER) / Error Vector Magnitude (EVM)
- Receiver (Uplink):
  - Sensitivity
  - Demodulation performance for different reference propagation channels and Modulation and Coding schemes (MCS)
  - Interference and blocking characteristics, according to TS 36.104:
    - In-band and out-of-band blocking: *"The blocking characteristics is a measure of the receiver ability to receive a wanted signal at its assigned channel in the presence of an unwanted interferer, which are either a 1.4MHz, 3MHz or 5MHz E-UTRA signal for in-band blocking or a CW signal for out-of-band blocking."*
    - Adjacent Channel Selectivity (ACS):*"Adjacent channel selectivity (ACS) is a measure of the receiver ability to receive a wanted signal at its assigned channel frequency in the presence of an adjacent channel signal with a*

specified centre frequency offset of the interfering signal to the band edge of a victim system."

Especially the last point is important for our study, because the allowed blocking levels for base stations depend strongly on the frequency separation between interfering signal and wanted carrier. Details of the 3GPP specifications are shown in the next subchapter.

Additionally to the existing base station and UE specifications, there are current activities in 3GPP on Railway Mobile Radio (RMR, the term in 3GPP for FRMCS):

- Introduction of band n100 at 900 MHz ([17], [20])
- Introduction of band n101 TDD at 1900 MHz for RMR [18] and Technical Report on the introduction of 1900 MHz NR band for Europe for Rail Mobile Radio (RMR) in Release 17 [22], referencing to CEPT [7] and ECC decisions [8]. Especially here, the following statements are to be mentioned:
  - *Chapter 7.1.3 Receiver Characteristics*
    - ***"RAN4 will not specify requirements related to the CEPT assumptions for BS enhanced selectivity operating adjacent to band n1 and deployed close by the corresponding railway infrastructure"***
  - Chapter 9 Deployment aspects
    - ***"In general, network deployment aspects are out of scope of the RAN4 work. For the derivation of the BS RF requirements it was assumed that the RMR and MFCN base stations are not co-located, and no coordination is necessary for RMR BS deployment."***
    - ***"Co-location of a MFCN BS and a RMR BS require coordination among the involved parties. The use of spectrum and its related conditions, e.g., EIRP, in accordance to ECC Decision (20)02 Part B [1], are in the responsibility of national regulation and coordination among involved parties."***
- The new WID for the introduction of high power UEs with a transmission power up to +31 dBm has been approved on the 3GPP RAN plenary in June 2022 [21]. The previous definition of the band n101 assumes a lower transmitter power of +23 dBm.
- Several **RF requirements related to band n101** have been introduced in March 2022 in TS 36.104, TS 37.104 and TS 38.104 for base stations, see the approved 3GPP RP-220376 with RAN4 Change Requests (CR) [23].
  - The CR for TS 38.104 for the 5G NR gNB includes
    - n101 base station rated output power: 51 dBm in 10 MHz to keep the limit of 65 dBm EIRP.
    - Regional Wide Area BS (operating band e.g. n1 and n101) basic unwanted emission limits: -15 dBm in 1 MHz measurement bandwidth. To our understanding, this requirement is not relevant, because the maximum frequency offset Δf_{OBUE} for the unwanted emissions is 10 MHz.
    - **Additional spurious emissions limits** for base stations in all bands (e.g. band 1, band 3) except n101:
      -52 dBm in 1 MHz @ 1900 to 1910 MHz. Note, that this limit is the same as it was already defined before for the overlapping band 33 (1900-1920 MHz)
    - **Spurious emissions limits** in 1920 to 1980 MHz for base station equipment operating in band n101:
      -57 dBm in 5 MHz.

- **Out-of-band blocking requirements for base stations in band n101** especially for interfering signal with centre frequencies between 1807.5 to 1877.5 MHz (= band 3): -20 dBm (5 MHz LTE signal)
- The CR for TS 36.104 for the LTE eNB includes
  - Base station spurious emission limits for E-UTRA BS in band n101 of -52 dBm in 1 MHz. Note, that this limit is the same as it was already defined before for the overlapping band 33 (1900-1920 MHz)
  - Spurious emissions limits and blocking performance requirements for Wide Area BS in n101, co-located with another BS.
- The CR for TS 37.104 includes coexistence requirements for band n101:
  - Base station spurious emission limits, same values as for TS 36.104 (see above)
  - Spurious emissions limits and blocking performance requirements for BS in n101, co-located with another BS.

As an explanation of the above mentioned requirements, TS 38.104 [13] states: *"**Unwanted emissions consist of out-of-band emissions and spurious emissions** according to ITU definitions [2]. In ITU terminology, out of band emissions are unwanted emissions immediately outside the BS channel bandwidth resulting from the modulation process and non-linearity in the transmitter but excluding spurious emissions. Spurious emissions are emissions which are caused by unwanted transmitter effects such as harmonics emission, parasitic emission, intermodulation products and frequency conversion products, but exclude out of band emissions."*

Adjacent Channel Selectivity (ACS) and Blocking levels in 3GPP

A visualization of the frequency separation for the MFCN case of a 20 MHz UL signal between 1920 – 1940MHz is shown in Figure 20. Also shown, depending on the frequency separation from the uplink channel edges, are the different interfering levels as specified in 3GPP [11], from -52 dBm with an LTE signal up to -15 dBm with a CW interferer:

- For the adjacent channel selectivity (ACS), a 5 MHz 3GPP E-UTRA carrier is assumed as interfering signal, at a frequency separation of 2.5 MHz from the band edges of the wanted signal
- for so called in-band blocking, a 5 MHz 3GPP E-UTRA carrier is assumed as interfering signal, at a frequency separation (from 7.5 MHz) up to 20 MHz from the band edges of the wanted signal
- for out-of-band blocking, a Continuous Wave (CW) signal is assumed as interferer with at least 20 MHz separation from the band edges of the wanted signal

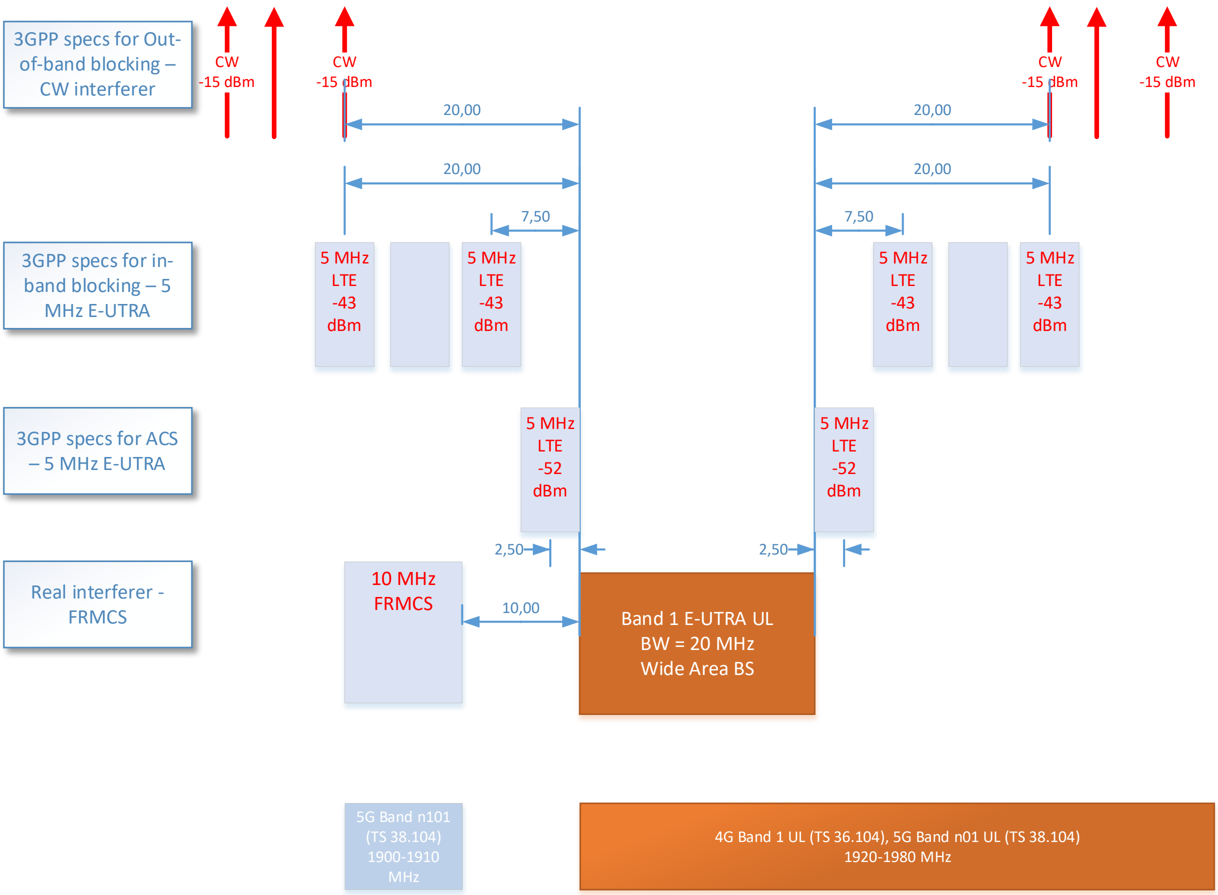

Figure 20: Visualization of LTE [11] 3GPP specifications for adjacent channel selectivity and blocking, in case of a 20 MHz LTE UL channel and wide area base station.

Figure 21 visualizes the frequency plan around 1900 MHz, the interfering signals and the LTE and 5G 3GPP specifications for the allowed blocking levels that are defined for different kind of base stations (wide area, medium range ≤ 38 dBm rated output power, local area ≤ 24 dBm, home ≤ 20 dBm).

The consequence, when the maximum interfering blocking levels are exceeded, are severe: Since the input RF stage of the base station with its input Low Noise Amplifier (LNA) and embedded filters will be overloaded in case of strong interference signals (e.g. over -43 dBm), the RF stage will be in non-linear operation mode, causing mainly 3rd order products ranging into the spectrum of the wanted uplink signal. The nature of non-linear 3rd order products of amplifiers is, that 1 dB more interfering signal leads to 3 dB more non-linear distorting signals. Thus, the weak wanted uplink signal (e.g. $P_{refsense}$ = -101.5 dBm) is distorted most likely on the complete wanted UL bandwidth, even for slightly exceeded allowed blocking levels.

In our study, the MFCN Uplink in 1920 – 1940MHz might be interfered by the FRMCS base station and/or by the cab-radios / UEs mounted on the train roofs.

Generally, out-of-band emissions from base stations and UEs are relevant as interfering source as well. However, the 3GPP specification for the blocking level with a frequency separation of up to 20 MHz is so restrictive with -43 dBm for wide area base stations, that this interfering effect is dominant over the out-of-band emissions (Adjacent Channel Leakage Ratio, ACLR) from the

FRMCS base station inside the MFCN uplink spectrum. As a comparison, the ACLR emissions are specified in 3GPP in [13] for a gNB to be -45 dBc and so the radiated power level in an adjacent channel by a base station is maximum +20 dBm EIRP at a carrier power of +65 dBm. This means, that the radiated power of a base station in the adjacent channel is at least 10 dB lower than the FRMCS UL transmission of a high power cab radio with up to +33 dBm.

It has to be noted that the specified blocking levels in 3GPP are the same for LTE eNB, LTE NB IoT eNB and 5G gNB in band 1 and 3. So, our analysis is valid for both the current LTE deployment as well as for a future 5G deployments by MFCN.

Observations from 3GPP specification:

- The specified maximum blocking level in 3GPP is depending on the frequency separation.
    - With at least 20 MHz separation, the allowed blocking level is -15 dBm for a CW interferer
    - At a separation of maximum 20 MHz, the maximum interfering level is -43 dBm.
- The maximum blocking level specifications are the same for LTE, LTE NB-IoT and 5G NR.
- 3GPP does not specify or intent to specify further enhanced selectivity for FRMCS scenarios as currently introduced for RMR.
- The dominant interference source with a frequency separation of 10 MHz is the carrier signal level of FRMCS of up to +65 dBm EIRP, being dominant over the interference by out-of-band emissions of the FRMCS carrier.
- The FRMCS high power cab-radio UE EIRP is up to +33 dBm and might lead to temporary interference due to the less spatial separation to the MFCN base stations and the higher time share of UL transmissions (UL:DL ratio 3 in FRMCS TDD configuration)

Recommendations from 3GPP specifications:

- For interference analysis- in coexistence scenarios of FRMCS and MFCN in Band 1, a maximum blocking level of -43 dBm as specified by 3GPP should be used.
- Further interference mitigation is essentially required especially in uncoordinated deployments.
- In the 3GPP specifications related to the new band n101 for FRMCS, measures to minimize interference on MFCN UL in band 1/n1 shall be considered. This is especially true for the Work Item on high power cab-radio [21]. This is in accordance with the recommendation in the report [6].

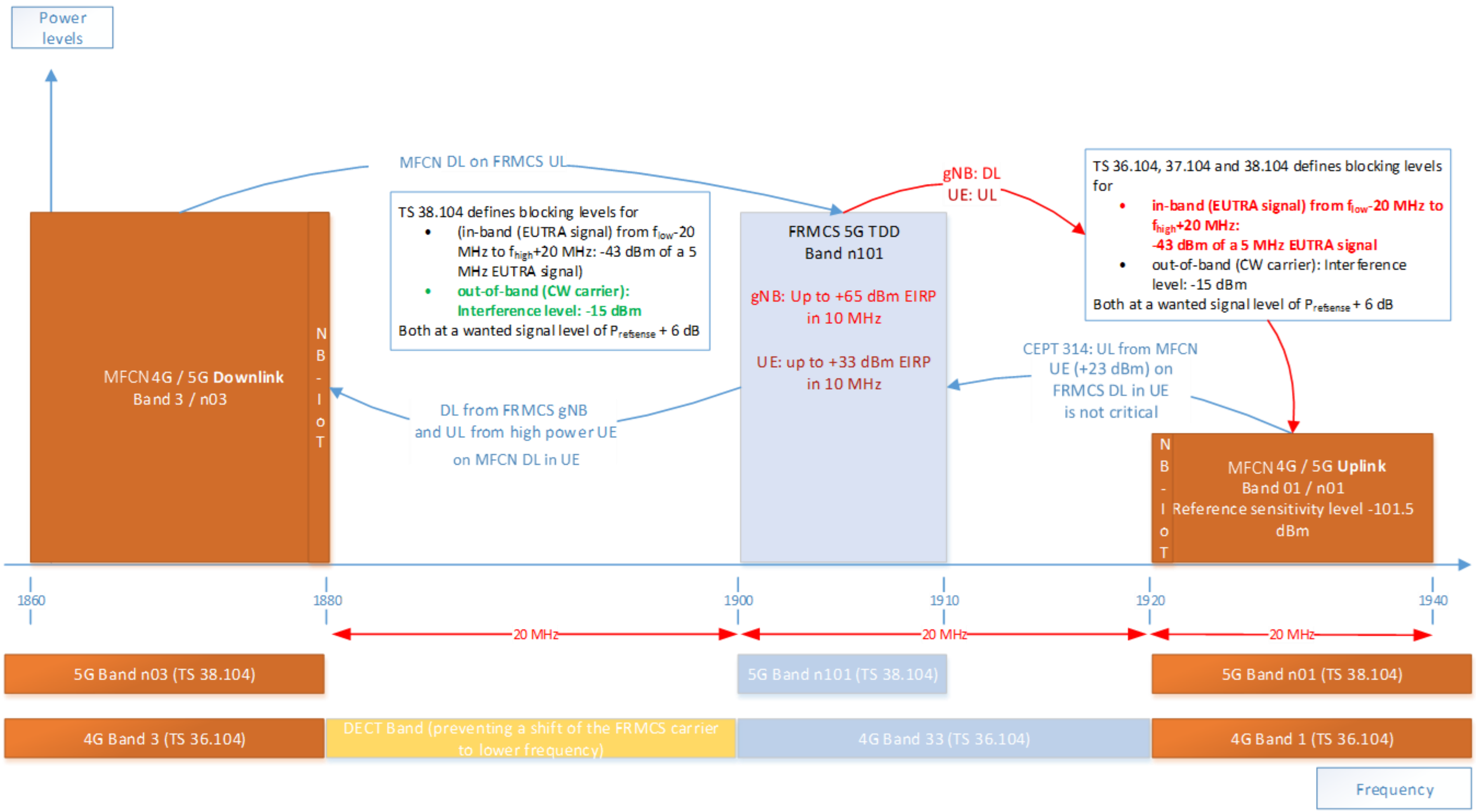

Figure 21: Visualization of various interference including the allowed blocking levels from the 3GPP standard and interfering power levels from CEPT reports. The critical interference path is marked in red.

7.3 ETSI Specifications

A new ETSI technical specification TS 103 807 was published in 2021 [26], "*addressing additional requirements arising from EC/CEPT spectrum regulatory framework, that apply to specific equipment in specific cases in certain countries and/or in certain geographical areas*".

The enhanced selectivity is going beyond the 3GPP specification of allowed blocking levels, especially for the scenario of an interfering signal in 1900 to 1910 MHz frequency range, on LTE and NR base stations in band 1/n1.

The general blocking levels are depicted in the following table:

Table 5: Enhanced selectivity specified in ETSI document [26]

Base station class	Mean power of interfering signal	Wanted signal mean power	Center frequency of interfering signal
Wide area BS	-30 dBm	$P_{Refsense}$ + 1 dB	1905 MHz
Medium Range BS			

Observations from ETSI specification:

Compared with the 3GPP specifications [9] for LTE and [10] for NR, this new ETSI specification…

- defines an maximum blocking level increased by 13 dB,
- with a more realistic interfering LTE/NR FDD signal for the scenario instead of a CW interference signal defined in 3GPP,
- at a lower level of the wanted uplink signal level ($P_{Refsense}$ + 1 dB instead of $P_{Refsense}$ + 6 dB), which is close to the achievable cellular coverage without any interference.

Recommendations from ETSI specifications:

- For future MFCN sites and upgrades of base station equipment at existing sites, the enhanced selectivity specifications from ETSI should be taken as a basis.

7.4 Further Literature

Scientific literature about interference and blocking levels is not relevant for this study, because 3GPP has a comprehensive set of performance specifications, which are applicable for BS and UE equipment manufacturers.

7.5 Conclusions from Literature Review

The CEPT report addressing the most relevant case of interference from FRMCS BSs in 1900-1910 MHz on the MFCN Uplink above 1920 MHz is the ECC Report 318 [6]. The focus therein is mainly on the unwanted emissions resulting to derive the LRTC in terms of BEM, **while the blocking levels or intermodulation are not investigated** (see [6]). Despite, the proposed BEMs involving high EIRP up to +65 dBm/10 MHz is **noted as a case needing very high selectivity for the MFCN BSs up to 40 dB more** compared to the 3GPP requirement.

Key observations and conclusions from CEPT 318 report are as follows:

- *Only non-AAS FRMCS and non-AAS MFCN systems have been considered. Additional studies should be performed in case AAS systems are considered for FRMCS in the 1900-1910 MHz band. The protection of MFCN 5G/NR with AAS BS above 1920 MHz was not studied in this Report. Further analysis of the interference impact of FRMCS on MFCN AAS systems may be required.*
- *As described in CEPT Report 19, the BEM is developed on the basis that detailed coordination and cooperation agreements would not be required to be in place prior to network deployment.* ***The BEM for the transmitter emissions would not avoid all interference that might arise in certain deployment scenarios, including for some configurations at shared base station sites or between nearby base station sites. In these situations, mobile network operators and RMR operators of both systems may have to coordinate, and the use of additional interference mitigation techniques might be considered.***
- *With the current level of selectivity of MFCN base stations, the defined LRTC for FRMCS may result in interference to some MFCN base stations located near FRMCS BS sites. One way of addressing this interference is to coordinate FRMCS and MFCN deployments. However,* ***this means that RMR operators may not be able to use 65 dBm at certain locations. If 65 dBm EIRP for uncoordinated FRMCS base stations is desired, then many MFCN BSs may need to be adapted when an FRMCS BS is rolled out in their proximity to minimize interference from FRMCS.***
- *Additional mitigation techniques need to be implemented on a case-by-case basis, such as adjustments of antenna directivity, azimuth, tilt, or improve the selectivity of the MFCN BS in the vicinity of the railway tracks.*
- *In order to ensure that the MFCN operators have enough time to adapt the relevant radio sites, the RMR operator is required to perform an early notification procedure in advance of the rollout of a new FRMCS BS.*
- In order to enable an in-block EIRP of 65 dBm/(10 MHz) for FRMCS BS, the MFCN BS selectivity would need to be 98.3 dB (assuming an MCL of 63 dB measured at the antenna connector), which is
  - 24.3 dB more selectivity compared that in the CEPT Report 39
  - 40.6 dB more selectivity in compared to that in the 3GPP TS 37 104.
- In order to enable an in-block EIRP of 65 dBm/(10 MHz) for FRMCS BS, the MFCN BS selectivity would need to be 88.3 dB (assuming an MCL of 73 dB measured at the antenna connector), which is
  - 14.3 dB more selectivity compared that in the CEPT Report 39
  - 30.6 dB more selectivity in compared to that in the 3GPP TS 37 104.
- The interference from FRMCS cab-radio of 31 dBm output power to MFCN uplink is acceptable when uplink power-control is implemented and activated.
- Co-located FRMCS and MFCN sites would lead to strong interference especially in the uplink of band 1, both with back-to-back installations of the antennas and with vertical separation of the antennas.

A recommendation based on the last point is

- that co-located installations of uncoordinated 5G TDD and 4G/5G FDD Base Stations would result in interference especially in the MFCN uplink frequency band 1 at 1920-1940 MHz and should be avoided.

Further, the consideration that **MFCN and RMR systems must coordinate to avoid interference by adapting the selectivity of the MFCN BSs**, is reiterated in the CEPT ECC Decision 20(20) [7] (where 65 dBm/10 MHz EIRP is decided as mandatory in-block requirement for uncoordinated deployment):

- *that the least restrictive technical conditions (LRTC) for wideband RMR in 1900-1910 MHz assume that MFCN base stations (BS) receiving above 1920 MHz have an enhanced selectivity compared to the current Harmonised European Standards, which would facilitate coexistence with RMR BS transmitting up to 65 dBm EIRP, and that current MFCN BS located near an RMR radio site may need to be adapted so that they do not suffer interference;*
- *that operators of commercial mobile networks in 1920-1980 MHz should have, sufficiently far in advance, information on the rollout of a new RMR BS in 1900-1910 MHz;*
- *that ECC Report 229 proposes a systematic approach based on a coordination/cooperation process and guidelines for the dialogue between RMR and MFCN licensees as well as with the spectrum administration and that CEPT Report 74 gives an example of a coexistence criterion as part of a national coordination procedure.*

There is no further specification on top of the 3GPP specifications available by the equipment vendors. The **further analysis in this report is assuming 3GPP specifications for sensitivity and maximum allowed blocking levels [11]**.

Key Observations from 3GPP specification:

- As the blocking levels are depending on the frequency separation between two carriers, the **most severe interference we expect from the FRMCS base station on the MFCN Uplink at 1920-1940 MHz, with an allowed blocking level of -43 dBm.**
- In opposite direction, the MFCN DL at up to 1880 MHz is separated by 20 MHz from the FRMCS Uplink at 1900-1910 MHz, leading to a higher allowed blocking level by 28 dB, to an absolute power level of -15 dBm.
- The maximum blocking level specifications are the same for LTE, LTE NB-IoT and 5G NR.
- The dominant interference source with a frequency separation of 10 MHz is the carrier signal level of FRMCS of up to +65 dBm, being dominant over the interference by out-of-band emissions of the FRMCS carrier.
- 3GPP does not specify further enhanced selectivity for FRMCS scenarios as currently introduced for RMR.
- The FRMCS cab-radio UE EIRP is up to +33 dB might lead to temporary interference due to the less spatial separation to the MFCN base stations and the higher time share of UL transmissions (UL:DL ratio 3 in FRMCS TDD configuration)

We assume the maximum allowed blocking level for base stations as the primary source for potential interference in coexistence scenarios of MFCN and the future FRMCS.

Main interference on the MFCN Uplink is expected by

- **The carrier signals of the permanently present FRMCS base stations**
- **The temporary interfering UE cab radios with quasi-omnidirectional antenna pattern**
  - with a distance lower than the FRMCS base stations,
  - with a transmitted power 32 dB lower than FRMCS gNB
  - with a greater time share of UL transmissions, compared to the DL transmissions of the FRMCS gNB (UL:DL is 3:1 according to [5])

Recommendations from 3GPP specifications:

- For interference analysis- in coexistence scenarios of FRMCS and MFCN in Band 1, a maximum blocking level of -43 dBm as specified by 3GPP should be used.
- Further interference mitigation is essentially required especially in uncoordinated deployments.

For our analysis in chapter 8.1, we assume the maximum allowed blocking level of -43 dBm and wide area base stations.

8 Interference Analysis in Coexistence Scenarios

This chapter will assess the interference power levels including propagation effects

- LOS / NLOS propagation when sites for FRMCS and MFCN are separated
- Realistic channel models for urban, suburban and rural environments, like Hata-Okumura path loss model.
- With and without antenna discrimination (few values, e.g. antenna gain values from antenna patterns in CEPT reports, and for 0°, 45°, 90° de-pointing of FRMCS and MFCN antennas)

8.1 Minimum Distance to keep Blocking Levels

Plotted in Figure 23 is the received signal power from the FRMCS BS transmissions in 1900–1910 MHz at the MFCN BSs (receiving in 1920–1940 MHz). The results are computed with the EIRP levels (see Figure 15, Figure 16 and Figure 17), the MCL equation and the EPM-73 path loss model discussed in Section 7.1.2; the parameters ($G_{Rail} = 14$ dBi, $G_{MFCN} = 15$ dBi and the total antenna discrimination $D_{Rail} + D_{MFCN} = 14$ dB, while varying the distance) are chosen from the table in reproduced in Figure 14. Specifically, the received power at MFCN BS from FRMCS BS transmissions (in 1900 – 1910 MHz) is computed as follows, in dBm:

$$\begin{aligned} \text{Received power } &= \text{FRMCS Total Radiated Power } - MCL \\ &= (\text{FRMCS EIRP} - G_{Rail}) - MCL \end{aligned}$$

which, with $MCL = PL_{(f,d)} - G_{Rail} - G_{MFCN} + D_{Rail} + D_{MFCN}$, simplifies to

$$\begin{aligned} \text{Received power } &= \text{FRMCS EIRP} - PL_{(f,d)} + G_{MFCN} - D_{Rail} - D_{MFCN} \\ &= \text{FRMCS EIRP} - PL_{(f,d)} + 15 \text{ dBi} - (D_{Rail} + D_{MFCN}) \end{aligned}$$

Also plotted for comparison are a couple of curves with the COST-Hata path loss model [16] (which is more applicable to BS-to-UE links). Note that the 3GPP blocking level requirement [11] of -43 dBm is not reached without sufficient selectivity through antenna discrimination (or achieved through additional filtering).

Yet, very large BS-BS separation in distance is needed to maintain the requirement.

Recall from Figure 13 that the vertical antenna discriminations depend on the distance between the BS sites, height difference of the BS sites and the down-tilts, while the horizontal antenna discrimination only depends on the orientation of the sector beams. Note that the horizontal antenna discrimination of each sector antenna at a BS site to a nearby FRMCs BS site vary with the orientation as indicated by Figure 22. For examples, considering the horizontal antenna pattern from Figure 18, a few possible horizontal discrimination values from the three sectors of an MFCN BS site are noted in Table 6.

Recommendations:

The examples for rotating the MFCN antenna sectors indicate, that some horizontal discrimination can also be achieved for even the worst sector at each MFCN site, if the sectors can be conveniently oriented, e.g. by 60°.

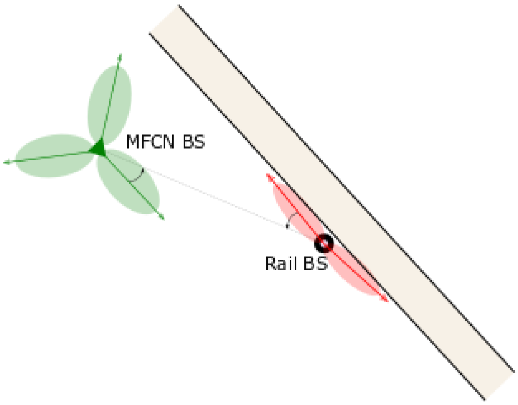

Figure 22: An example depiction of the possible horizontal antenna discrimination between nearby MFCN and FRMCS BS sectors.

Table 6: Example horizontal antenna discriminations from the MFCN BS sectors assuming the horizontal antenna gain pattern from Figure 18.

BS site orientations	Azimuth angle between sector and FRMCS BS (degrees)	Horizontal antenna discrimination (dB)
Example 1	0	0
	+120	-30
	-120	-30
Example 2	+30	-2.5
	+150	-30
	-90	-23
Example 3	+60	-10.2
	+180	-30
	-60	-10.2
Example 4	+90	-23
	-150	-30
	-30	-2.5

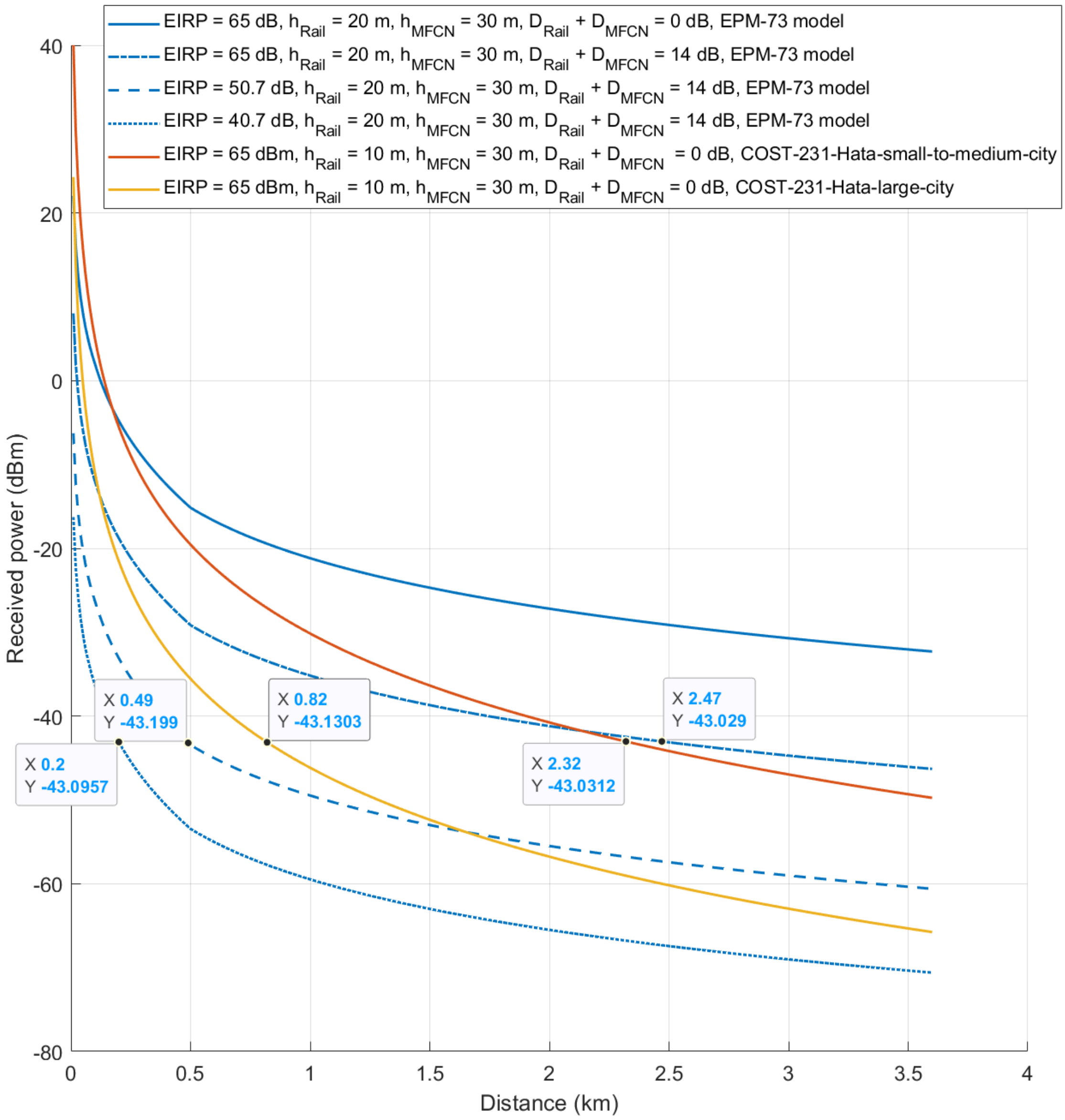

Figure 23: Received power at MFCN BS from FRMCS BS transmissions, subject to path loss models and assumed BS heights. Data tips indicating points where the blocking-level requirement of -43 dBm for MFCN BS in the 1900–1910 MHz band is met, ranging from 200 m to 2470 m; EPM-73 channel model assuming no antenna discrimination requires >>3.5 km separation distance.

With the same assumptions and parameters settings as in the previous plot, but varying the discrimination (achieved through antenna depointing and/or additional RF filtering), Figure 24 plots the required distance for meeting the -43 dBm blocking level requirement.

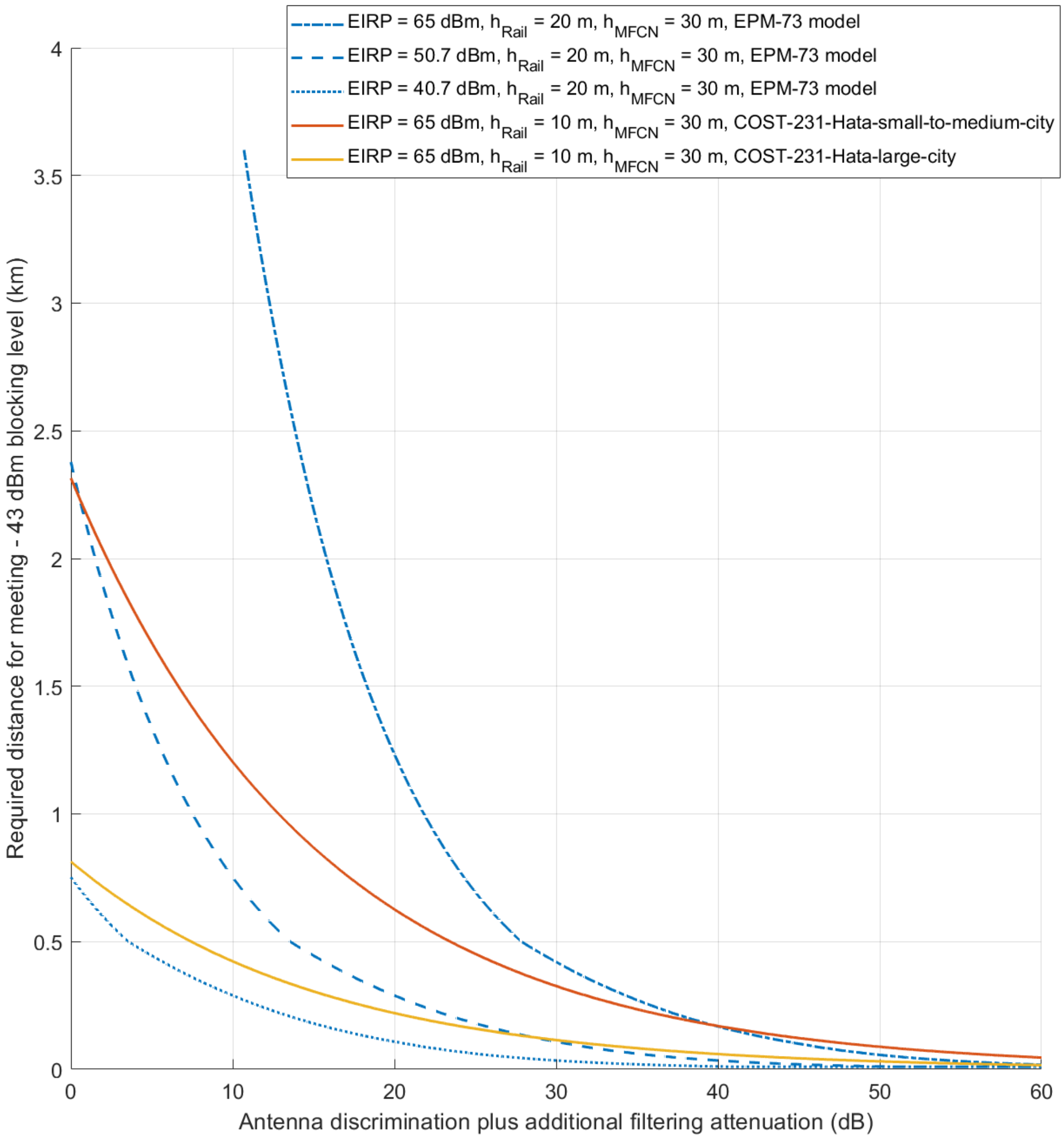

Figure 24: Required distance for meeting -43 dBm blocking level (km), given the level of antenna discrimination and/or additional filtering attenuation. EPM-73 as used in CEPT reports is a LoS model, and COST-231 is a channel model defined for mobile base station links.

For other MFCN uplink channels with the FRMCS channel falling farther away (below than F_{UL_low} - 20 MHz or above F_{UL_high} +20 MHz, like MFCN bands 3, 7, 20, 28, 78), the allowed blocking level for a CW interfering signal can be as high as -15 dBm according to 3GPP specifications.

We have provided in the next figure the required distance with -15 dBm blocking level for comparison, assuming, that the behaviour of a base station is the same for a 5G interfering carrier at 10 MHz separation as for a CW interferer with a frequency separation of at least 20 MHz.

Observations:

No additional antenna discrimination and/or RF filtering is required for a frequency separation of more than 20 MHz for a separation distance of 370 m with an NLoS path loss model for base stations and for a separation distance of 500 m with a LoS propagation model as used in CEPT reports.

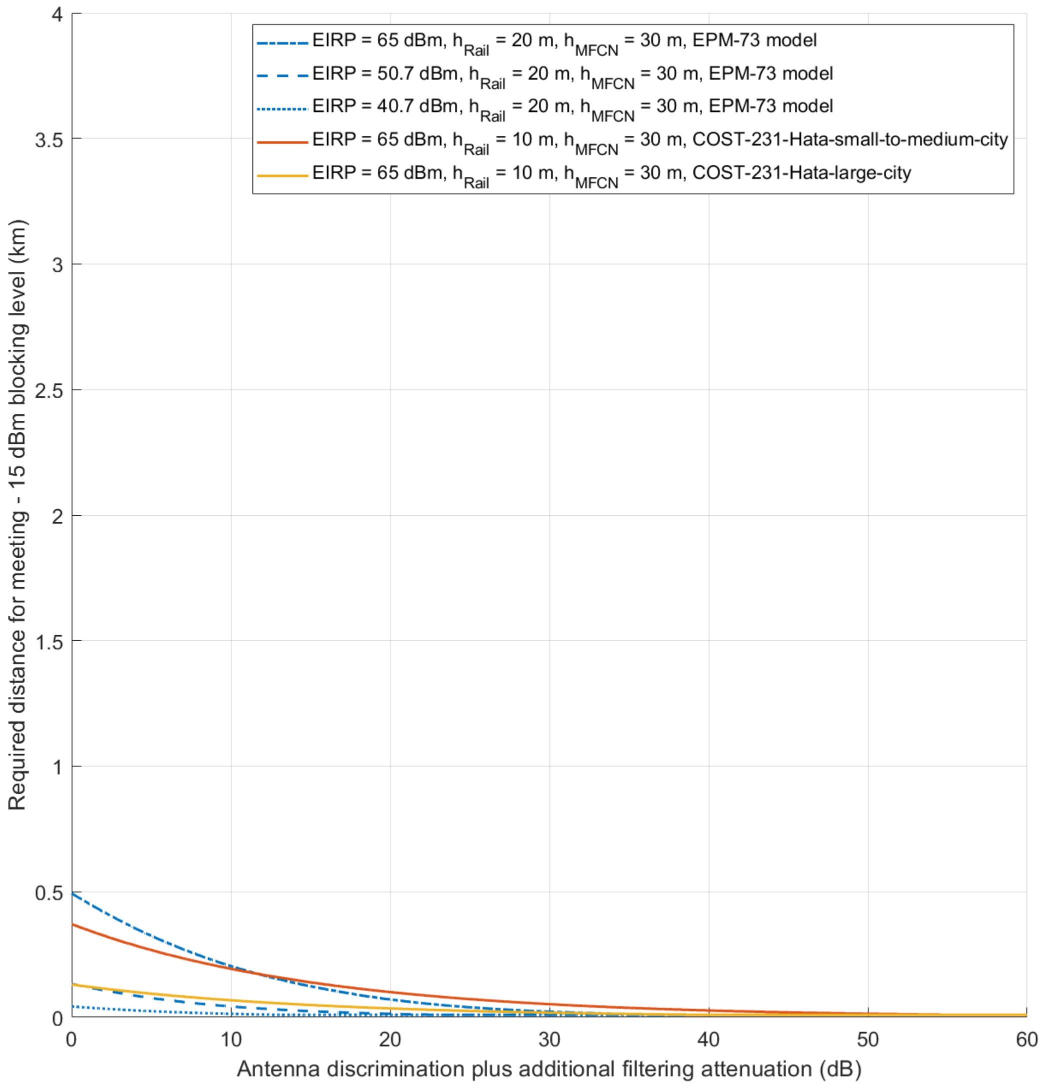

Figure 25: Similar figure on the required distance as the previous one, but for an increased -15 dBm blocking level as specified by 3GPP for a frequency separation of more than 20 MHz, given the level of antenna discrimination and/or additional filtering attenuation. This figure is relevant for other Uplink bands by MFCN, but not the band 1/n1.

8.1.1 Relevance of Blocking Levels for MFCN Base Stations

Noted in Table 7 is the minimum discrimination and/or filtering attenuation needed for meeting the -43 dBm blocking level requirement for a given BS separation between MFCN and FRMCS, from the results in Figure 24 with the EPM-73 path loss model.

Note that the 3GPP compliance to the blocking level requirement means that the BSs should be able to block an interferer below -43 dBm, in the 1900—1910 MHz band. Therefore, antenna discrimination and/or filtering attenuation additional to the path loss would be needed for many MFCN BS as noted above; e.g., MFCN BSs with an FRMCS BS (emitting +65 dBm EIRP) closer than 1 km should have at least 21.9 dB additional loss.

Observations from Blocking Level Analysis:

- Additional interference mitigation like antenna discrimination and/or filtering is required even for a distance separation between FRMCS and MFCN of more than 3 km.

Table 7: Minimum discrimination + filtering attenuation needed for meeting the -43 dBm blocking level requirement for the given BS separation between MFCN and FRMCS (GSM-R). The EPM-73 path loss model is considered.

Distance between MFCN BS and closest FRMCS BS (km)	Needed antenna discrimination + filtering attenuation at MFCN BS (dB)		
	FRMCS EIRP = 65 dBm	FRMCS EIRP = 50.7 dBm	FRMCS EIRP = 40.7 dBm
< 0.1	> 45	> 30.7	> 20.7
< 0.3	> 34	> 19.7	> 9.7
< 0.5	> 27.9	> 13.6	> 3.6
< 1	> 21.9	> 7.6	≥ 0
< 2	> 15.9	> 1.6	≥ 0
< 3	> 12.3	≥ 0	≥ 0
< 3.6	> 10.7	≥ 0	≥ 0

8.2 Conclusions and potential Interference Mitigation

Conclusion#1: Interference direction of FRMCS and MFCN networks

Interference of MFCN DL on FRMCS UL is less harmful due to a difference in the allowed interference level of 28 dB (which is equivalent to a distance factor of 25 under LoS conditions) between the allowed interference levels of -43 dBm and -15 dBm.

Conclusion#2: Interference by FRMCS UEs

Interference of FRMCS UE on MFCN UL is still harmful, even, when UE EIRP (+33 dBm) is 32 dB lower than from gNB, because UE might pass-by at MFCN gNB, with much smaller distance to

MFCN gNB. However, the interference would be limited in time for the pass-by of the train, but potentially higher in time share due to the asymmetric UL:DL ratio 3 of planned FRMCS.

Minimum LoS distance is 450m, (assuming both antenna main lobes) to keep -43 dBm blocking levels.

Conclusion#3: Interference by FRMCS gNBs

Interference of the FRMCS gNB on the MFCN UL is the major problem when FRMCS will be deployed as described in the CEPT reports.

The strong FRMCS carrier counts as interfering signal. To keep the interference level of -43 dBm, a theoretical distance of several km would have to be kept under LoS conditions (assuming the Tx and Rx antenna main lobes).

We observe from blocking level analysis that:

- Additional interference mitigation like antenna discrimination and/or filtering is required even for a distance separation between FRMCS and MFCN of more than 3 km.

Conclusion#4: Lab measurements with real equipment

The effect of interference might depend on the specific location of the interfering signal at a frequency location from 10 to 20 MHz apart of the uplink carrier, and the real achieved maximum blocking power levels might deviate/exceed 3GPP specification.

Therefore, **measurements with the existing MFCN base station equipment** are recommended, e.g. with a micro core network and with an unsynchronized interfering 5G gNB with the specific TDD configuration of FRMCS (TDD, UL to DL ratio 3:1).

As a result, the interference effects like power levels and influence of the frequency locations are better understood and several interference mitigation techniques despite of **the antenna discrimination** can be optimized in regard of effort and costs, like **additional filtering**, and/or the 3GPP defined feature ***Additional-Maximum Power Reduction*** **(A-MPR)** for reduced power of Resource Blocks in the Uplink transmissions nearer to the MFCN spectrum.

These measurements could be done with a conducted setup in the lab to have well defined power levels of wanted uplink and interfering signals. An additional interfering 5G base station can be implemented e.g. with a Software Defined Radio gNB.

Conclusion#5: Benefit of additional Filters

Introducing additional notch filters to suppress the FRMCS carrier at 1900 to 1910 MHz will decrease the interference levels significantly (better than other interference mitigation methods) and would work with any multi-band base station.

As an example, considering the worst case in Figure 24, i.e., with FRMS BS transmitting at +65 dBm EIRP under the EPM-73 path loss model, note that with antenna discrimination alone (~ 10 dB), the required spatial separation between MFCN and FRMCS sites is above 3.6 km.

By introducing a notch filter , for example by adding 40 dB more attenuation, the required spatial separation becomes only 56 meters.

Using such a filter would of course be with the penalty of passband losses reducing effective DL carrier power as well as uplink sensitivity.

9 About Fraunhofer IIS

The Fraunhofer-Gesellschaft, based in Germany, is the world's leading applied research organization. By prioritizing key technologies for the future and commercializing its findings in business and industry, it plays a major role in the innovation process. A trailblazer and trendsetter in innovative developments and research excellence, it is helping shape our society and our future.

Founded in 1949, the Fraunhofer-Gesellschaft currently operates 76 institutes and research units throughout Germany. More than 30,000 employees, predominantly scientists and engineers, work with an annual research budget of roughly 3 billion euros, 2.6 billion euros of which is designated as contract research.

The Fraunhofer Institute for Integrated Circuits IIS is one of the world's leading application-oriented research institutions for microelectronic and IT system solutions and services. It ranks first among all Fraunhofer Institutes in size. With the creation of mp3 and the co-development of AAC, Fraunhofer IIS has reached worldwide recognition. In close cooperation with partners and clients the Institute provides research and development services in the following areas: Audio & Multimedia, Imaging Systems, Energy Management, IC Design and Design Automation, Communication Systems, Positioning, Medical Technology, Sensor Systems, Safety and Security Technology, Supply Chain Management and Non-destructive Testing.

Thomas Heyn received his degree in Electrical Engineering (Dipl.Ing.) from Friedrich-Alexander-University in Erlangen in 1996 and joined Fraunhofer IIS shortly after. Initially, he implemented several communication standards for satellite and terrestrial wireless transmissions, based on Software-Defined Radio platforms and carried out different field trials for performance assessments and propagation channel modeling. Since 2001, he is head of the Mobile Communications Group within the Broadband and Broadcast Department. As a 3GPP delegate for Fraunhofer IIS since 2015 mainly for the RAN Plenaries, he was one of the first within 3GPP to integrate Non-Terrestrial-Networks and satellite into the new mobile communications standard. Currently Mr. Heyn and his team are pursuing this goal in RAN1, RAN2 and RAN3. Furthermore, Thomas Heyn was one of the initial driving forces behind Fraunhofer joining OSA (Open Air Interface Software Alliance) especially for the implementation of 5G New Radio on gNB and UE side, based on the open source stack OpenAirInterface.

Dr. Geordie George received the M.Tech. degree in electrical engineering from the Indian Institute of Technology Madras, Chennai, India, in 2007, and the Ph.D. degree in information and communication technologies from Universitat Pompeu Fabra (UPF), Barcelona, Spain, in 2017. From 2009 to 2011, he was a Research Engineer with the Center of Excellence in Wireless Technologies, Chennai, India, where he worked on the evaluation of the 4G standards, IEEE 802.16m and 3GPP LTE-A. He was a Post-Doctoral Researcher with UPF, from 2017 to 2018. In 2018, he joined the Fraunhofer Institute for Integrated Circuits IIS, Erlangen, Germany, where he is a Chief Scientist and 3GPP RAN1 delegate within the Broadcast and Broadband Department, working in 5G NR technologies and development of a simulation framework for 5G New Radio for different applications. His research interests are in the areas of communication theory, signal processing and energy saving, with a focus on the link- and system-level analysis and simulation of wireless communication systems.

10 Annex – Propagation Models

Propagation Models for analysis of Minimum Distance

Although the EPM-73 path loss model considers two break points with the lower one (d_1) defined in kilometres as

$$d_1 = 1.1 \times h_1 \times h_2 \times \frac{f}{3.47 \times 10^5},$$

where h_1 and h_2 are the BS antenna heights in meters and f is the frequency in MHz. It is noted (see the table from [6] reproduced in Figure 26) that the relevant distances for the evaluation are always less than d_1. Thus, the following formula applied for the pathloss at 1900 MHz is given in [6] as follows:

$$PL_{1900\ \mathrm{MHz}}(d,f) = PL_{\mathrm{freespace}}(d,f) \qquad d \leq 0.1\ \mathrm{km}$$

$$PL_{1900\ \mathrm{MHz}}(d,f) = PL_{\mathrm{freespace}}(d,f) + \left[\frac{d_{\mathrm{km}} - 0.1}{0.4}\right] \times 2.5 \qquad 0.1\ \mathrm{km} < d \leq 0.5\ \mathrm{km}$$

$$PL_{1900\ \mathrm{MHz}}(d,f) = PL_{\mathrm{freespace}}(d,f) + 3.2 \qquad d > 0.5\ \mathrm{km}$$

where:

$$PL_{\mathrm{freespace}}(d,f) = 32.4 + 20\log_{10}(f_{\mathrm{MHz}}) + 20\log_{10}(d_{\mathrm{km}})$$

Table 11: EPM-73's first break point calculation

	Urban	Rural
h_1 (RMR)	20 m	35 m
h_2 (MFCN)	30 m	45 m[13]
d_1 at 920 MHz	1.75 km	4.6 km
d_1 at 1900 MHz	3.6 km	9.5 km

Figure 26: Table from showing the first breaking point in the adopted path loss model, for the assumed BS heights of RMR/FRMCS and MFCN

Besides the above, note we have computed the results also with the standard propagation channel COST-231, defined for BS-to-UE links in large- and small-to-medium urban scenarios, details of which can be found in [16].

***** End of document *****