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Contents

1 Introduction

The purpose of this report is to help railway Infrastructure Managers (IMs) to understand and to provide guidance on various technical aspects related to the FRMCS Radio Access Network (RAN).

Another purpose of the report is to provide input for the spectrum related specification work of the FRMCS system. This document focuses on radio coverage and on-board aspects. Other RAN relevant aspects (as described in chapter 5) are still under study by UGFA.

Being specified as a 5G technology-based radio network, the FRMCS network benefits from capabilities significantly enhanced compared to 2G GSM-R that however also necessitate a rather more complex design path for the FRMCS radio network.

A good understanding of the characteristics and capabilities of a 5G NR network should enable IMs to determine the best design approach for (parts of) their FRMCS network, needed to optimise performance and costs. It should be noted that many subjects addressed in this document may apply to both the migration and post-migration phases of an FRMCS radio network, while some specific subjects may only be relevant for the FRMCS migration phase.

Based on the EU Decision 2021/1730 [Ref 1], which itself is based on ECC Decision (20)02 [Ref 2], Member States shall designate and make available on a non-exclusive basis radio spectrum for FRMCS in the 900 MHz and 1900 MHz frequency bands, i.e., 3GPP bands n100 and n101. Both bands are intended to be used as the main FRMCS frequency bands both during and after the migration from GSM-R to FRMCS for FRMCS critical applications. The main body of this document will only address the usage of these two bands for FRMCS.

This document should be read in conjunction with another UGFA working document, the O-8856 UGFA Whitepaper on migration scenarios[1].

As it is expected that over time additional insight and subjects will be developed, this document is a living document.

[1] O-8856 - UGFA Whitepaper on migration scenarios (ISBN 978-2-7461-3390-7)

2 Overview FRMCS specific regulation / specifications / reports

2.1 EU and CEPT ECC

The spectrum regulation applicable in Europe to the use of RMR paired frequency bands 874.4-880.0 MHz and 919.4-925.0 MHz and the RMR unpaired frequency band 1900-1910 MHz (i.e., n100 and n101) is defined in:

- 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). Approved 20 November 2020
- COMMISSION IMPLEMENTING DECISION (EU) 2021/1730 of 28 September 2021 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 1900-1910 MHz for Railway Mobil

2.2 3GPP

From the Radio Access Network (RAN) perspective, the following 3GPP documents are relevant:

- TR 38.852. 3rd Generation Partnership Project; Technical Specification Group Radio Access Network; Introduction of 1900MHz NR band for Europe on Rail Mobile Radio (RMR) (Release 17)
- TR 38.853. 3rd Generation Partnership Project; Technical Specification Group Radio Access Network; Introduction of 900MHz NR band for Europe on Rail Mobile Radio (RMR) (Release 17)
- The following TSs have been updated to reflect FRMCS specific capabilities:

TS/TR No.		TS/TR No.	
38.101-1		38.101-4	
38.104		38.104	
38.113		38.133	
38.124		38.141-1	
38.133		38.141-2	
38.211		37.141	
38.212			
38.213			
38.214			
38.300			
38.306			
38.307			
38.331			
38.423			
38.473			

Table 2-1: 3GPP documents

2.3 ETSI

From the Radio Access Network (RAN) perspective, the following ETSI documents are relevant:

- TR 103 554-2 Rail Telecommunications (RT), Next Generation Communication System, Radio performance simulations and evaluations in rail environment, Part 2: New Radio (NR);
- TR 103 865 Railway Telecommunication (RT), Future Rail Mobile Communication System (FRMCS), Radio performance aspects[2];
- TS 103 793 Rail Telecommunications (RT), Future Rail Mobile Communication System (FRMCS), FRMCS Radio Characteristics[3].

2.4 Document status

Documented listed in Sections 2.2 and 2.3 may be updated due to changes in the regulatory domain and/or further developments in the 3GPP and ETSI reports and specifications, the reader is expected to verify the actual status of the relevant documents and assess the impact of any such alterations.

[2] Work on this document is ongoing, current latest version of TR 103.865 is draft V0.0.12

[3] Work on this document is ongoing, current latest version is based on Release 17

3 Radio coverage

3.1 Services based coverage

3.1.1 Differences between GSM-R and 5G NR

GSM-R was originally designed where a single coding scheme was used for voice calls. Variable MCS (Modulation and Coding Scheme) was later introduced with GPRS, and further enhanced with each newer technology (EDGE, etc.). This, and the minimal number of deployment and configuration options, allowed for a relatively straightforward relationship between GSM-R coverage levels and the expected throughput values.

5G NR has many more options, therefore much higher complexity than GSM in these aspects: used channel BW, variable actual used bandwidth due to resource block scheduling, number of antennas / transmission panels, MIMO variations, TDD frame structures, configurable reference signals, CQI reporting and link adaptation, etc.

Additionally, black boxes are also present in the system, which are left up to implementation and not covered by the 3GPP specifications: most notably, the scheduler. This result in a complex relationship between coverage levels and achievable throughput depending on deployment strategy unlike a traditional linear relationship in GSM-R between coverage levels and its throughput.

For the successor of GSM-R, the 5G NR based FRMCS it is necessary to define a minimum performance level of the radio network to enable railway interoperability as this is dependent on the performance of both the on-board and track side radio equipment.

Such a minimum performance level of the FRMCS air interface is also necessary to enable a proper radio network design to support the critical FRMCS applications. Furthermore, a minimum quality level for the FRMCS radio signal is needed to determine criteria for coexistence with other radio networks in adjacent frequency bands.

Based on these requirements, UGFA started working with ETSI TC RT already in 2017 (see O-8789 LS from UGFA to ETSI TC RT on signal quality, submitted to ETSI in RT#70 as RT(18)068033).

Essential parameters for radio network design of the FRMCS air interface are:

- NR RSRP: SS-RSRP and CSI-RSRP
- NR RSRQ: SS-RSRQ and CSI-RSRQ
- SINR: SS-SINR and CSI-SINR

(Where SS stand for Synchronisation Signal, CSI stand for Channel State Information and SRS stands for Sounding Reference Signal).

Category	Physical Signal for Measurement
RSRP	SS reference signal received power (SS-RSRP)
	CSI reference signal received power (CSI-RSRP)
	SRS reference signal received power (SRS-RSRP)
RSRQ	SS reference signal received quality (SS-RSRQ)
	CSI reference signal received quality (CSI-RSRQ)
SINR	SS signal-to-noise and interference ratio (SS-SINR)
	CSI signal-to-noise and interference ratio (CSI-SINR)

Table 3-1: Important air interface relevant FRMCS radio network parameters for design purposes and measurements

Important differences between GSM-R and 5G NR in terms of power definition and measurements must be considered. Due to the fact that every FRMCS base station and mobile station is transmitting on the same DL or UL frequency (for FDD operation in band n100) or all FRMCS network elements are operating in the same band (for TDD operation in band n101), measurements and radio network planning based solely on received power figures are completely misleading.

The effects of intra system interference require special attention during the radio planning of the FRMCS air interface. In 5G NR, SINR seems to be an important parameter. SINR is the ratio of the received signal power to the summation of the average total interference power from the other FRMCS cells plus the background noise. SNR is the ratio of the received signal power to the background noise. Finally, SINR/SNR will be the most important factor for FRMCS throughput and service assurance.

FRMCS throughput on the air interface is determined by a combination of feasible modulation coding scheme and code rate. The achievable throughput corresponds to the result of channel estimation and will be expressed by the parameter CQI (Channel Quality Information). The following table provides a good overview of the relationship between CQI and SNR:

CQI	MCS	Code rate × 1024	Spectral efficiency	SNR (dB)	
				Perfect channel estimation	Practical channel estimation
1	QPSK	78	0.1523	-11.2	-6.3
2	QPSK	120	0.2344	-6.9	-5.8
3	QPSK	193	0.377	-2.2	-1.4
4	16QAM	308	0.6016	2.7	3.9
5	16QAM	449	0.877	4.3	5.3
6	16QAM	602	1.1758	6.9	8.1
7	64QAM	378	1.4766	8.5	9.8
8	64QAM	490	1.9141	10.6	11.7
9	64QAM	616	2.4063	12.4	13.6
10	64QAM	466	2.7305	14.4	15.8
11	64QAM	567	3.3223	17.5	18.8
12	256QAM	666	3.9023	18.1	21.4
13	256QAM	772	4.5234	20.2	23.6
14	256QAM	873	5.1152	22.8	28.2
15	256QAM	948	5.5547	24.9	32

Table 3-2: CQI – MCS relationships - Source: A. K. Thyagarajan, P. Balasubramanian, V. D and K. M, "SNR-CQI Mapping for 5G Downlink Network," 2021 IEEE Asia Pacific Conference on Wireless and Mobile (APWiMob), Bandung, Indonesia, 2021

3.1.2 Minimum FRMCS throughput requirements

As a key principle for FRMCS as a 5G network, and different from GSM-R, the data throughput that is required to support the minimum set of services on a specific rail track determines the minimum coverage requirements at cell edge between two adjacent FRMCS cells.

The basic procedure for determining the minimum FRMCS throughput requirements is described in section 3.1.4. This chapter proposes a FRMCS theoretical rail use case with the relevant traffic handling capacity needs. This theoretical use case consists of an operational railway scenario plus an estimation of the required up- and downlink capacity per running train and considering of the signalling per FRMCS radio cell. For the design of the FRMCS air interface the reference case, together with the overall FRMCS QoS requirements, may be used for the determination of the FRMCS coverage quality in the form of a minimum RSRP, RSRQ and SINR.

It should be noted that the FRMCS theoretical rail use case is independent from actual migration strategies of the Infrastructure Managers. Adjustments and additions need to be made at the national level.

3.1.3 Throughput Definitions

ECC Reports 341 provides a good description for throughput in the context of possible metrics that can be used to evaluate 5G NR coverage availability and performance[4].

Throughput represents the amount of data sent or received over a certain period of time. It needs to be defined at the layer at which data delivery is counted (application layer, IP layer, MAC layer or physical layer) and at which end of the communication (from UE perspective or from RAN perspective). Throughput on the UE side could be defined as the main performance indicator that reflects the actual end user experience when using mobile network services. Throughput on the RAN side gives an indication of how efficient the network is at handling data traffic. Throughput as a 5G NR metric is only applicable for active measurements. It is not applicable for IDLE mode coverage. It provides a good representation for CONNECTED mode coverage.

Application Layer Throughput
Application layer throughput is the most user experience-oriented point of observation, but it will have a higher dependency on the server being accessed. Application layer throughput from UE perspective is usually available in drive test tools and crowdsourcing applications.

IP Layer Throughput
Also referred to as PDCP SDU throughput, IP layer throughput is a common metric when using network performance management counters based KPIs, both from the RAN perspective and UE perspective (i.e., an average of all UEs in the cell). At IP level it is not possible to separate the contributions of different NR carriers in aggregation.

MAC Layer Throughput
MAC layer throughput is another common metric when using network performance management counters based KPIs, both from the RAN perspective and UE perspective (i.e., an average of all UEs in the cell). At the MAC layer, it is possible to differentiate the contribution of different NR carriers in aggregation.

Physical Layer Throughput
The lowest layer throughput (PDSCH/PUSCH) is the point of observation with the highest correlation with other network metrics. It is important to note that this reference does not consider retransmissions at higher layers. Specifically, a typical Block Error Rate of 10% at MAC layer would make physical layer throughput appear 10% better than it actually is for higher layers. Physical layer throughput from the UE perspective is typically available in Drive Test tools.

[4] This ECC Report highlights the main differences between 5G NR and previous mobile radio generations that make the so far commonly used signal strength coverage metric insufficient to assess 5G coverage.

3.1.4 Traffic load by FRMCS theoretical use case

The starting point for the derivation of the traffic load for individual FRMCS radio cells is the minimum throughput requirement per train. By using the GoA2 scenario (i.e. Voice[5] + ETCS L2 + ATO) in combination with the minimum throughput requirements as per Annex A.5 of AT-7800 v1.2.0, the figure for the throughput requirements is defined. Additionally, the throughput requirements based on signalling per FRMCS radio cell must be considered (see also Annex A.5 of AT-7800 v1.2.0).

This GoA2 scenario results in a required minimum application layer throughput of 95 kbps (in both downlink and uplink) that needs to be supported for each train. Assuming similar figure for the IP Layer throughput it must be noted that the corresponding physical layer throughput will be higher. In addition of that throughput per train, the FRMCS radio cell wide throughput figure for signalling has to be considered. For the GoA2 scenario, a throughput figure of 100 kbps in the downlink and 10 kbps in the uplink has to be added (see also Annex A.5 of AT-7800 v1.2.0).

According to FRMCS FRS requirements, voice communication shall support at least 10 participants to talk at the same time (i.e. 4 train driver voice links + 6 additional voice links). This requirement as a worst-case-scenario per FRMCS radio cell must be considered for total cell load as well.

For calculation of total cell load, assumptions on Inter-Site Distance (ISD) are necessary. According to ETSI TR 103 554-2, theoretical figures of 4 km at 900 MHz and 2 km at 1900 MHz are proposed here.

For the train traffic pattern, a scenario of a conventional line in a rural environment are proposed[6]. The number of trains based in a double track layout is 0.5 trains/km/track. Based on the assumption that the 900 MHz FRMCS radio cell has 2 km of track coverage for example by transmitting in 2 directions along the railway tracks, the total number of trains = 2 km * 2 tracks * 0.5 train/km/track = 2 trains. With these input figures the individual calculations of the traffic load for band n100 (900 MHz) and band n101 (1900 MHz) FRMCS radio cells can be performed (See also section 3.2.2.9 on Cell Edge Bitrates and Cell Throughput). It should be noted again that these application layer throughput numbers do not include additional overhead as probably needed by the physical layer.

3.1.4.1 Alignment with ERA on the minimum set of services

For interoperable tracks the minimum coverage requirements must be based on the minimum service requirements defined by the ERA as reflected in the CCS TSI. Note that this is FFS.

For other railway tracks the IM should determine the service requirements and hence the coverage requirements based on national or regional needs.

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[5] Alignment within the UIC working groups to use EVS_SWB with 24.4 kbps Codec Bit Rate, see also Annex A.5 of AT-7800 v1.2.0. Resulting application layer throughput is 45 kbps (Aggregation of voice codec bitrate with IP and RAN/real time header overheads, without header compression; Header compression can reduce application layer throughput to ~31 kbps).

[6] Most unfavourable conditions for that scenario: 2 trains crossing at cell edge & 2 trains near the radio site; Train speed of up to 160km/h.

3.2 Radio link budget

3.2.1 Definitions

Term	Description
BLER	Block Error Rate
B_{LNF}	Log Normal Fading margin
BS	Base Station
CSI-RS	Channel State Information Reference Signals
DL	Downlink
DMRS	Demodulation Reference Signal
FER	Frame Error Rate
G_a	Antenna Gain
ISD	Inter Site Distance
L_f	Feeder Cable loss
L_J	Jumper Cable loss
LNF	Lognormal Fading
L_{other}	Train roof and other losses
L_p	Propagation Loss
L_{UE}	UE Cable loss
MIMO	Multiple Input Multiple Output
NF (N_f)	Noise Figure
NR	New Radio
OFDM	Orthogonal Frequency Division Multiplex
PDCCH	Physical Downlink Control Channel
PDSCH	Physical Downlink Shared Channel
P_{nom}	TX Power
PRACH	Physical Random Access Channel
PUSCH	Physical Uplink Shared Channel
RB	Resource Block
RF	Radio Frequency
Rx	Receive
SCS	Sub Carrier Spacing
Tx	Transmit
UE	User Equipment
UL	Uplink

3.2.1.1 Frequency and Time Domain Structure

A transmitted OFDMA signal can be carried by a number of parallel subcarriers, each with a subcarrier spacing Δf_{SCS} (Hz). In NR, Δf_{SCS} is configurable as multiples of 15 kHz using the following:

$$\Delta f_{SCS} = \quad 2^{\mu} \times 15 \ \ [\text{kHz}]$$

Where μ =0,1,2,3,4 and is known as the numerology of the OFDM signal.

Twelve subcarriers are grouped into a resource block.

$$\Delta f_{RB} = 2^{\mu} \cdot 15 \cdot 12 \ \ [\text{kHz}]$$

Depending on numerology, μ, the resource block bandwidth, Δf_{RB} , will vary. Typical numerologies currently supported in NR systems are listed in Table 3-3 for NR Frequency Range 1 (< 7.25 GHz).

Frequency Range	Numerology (μ)	Resource Block Bandwidth	Subcarrier Spacing	Subcarriers per RB	Slot duration
FR1 FDD	0	180 kHz	15 kHz	12	1 ms
FR1 TDD	1	360 kHz	30 kHz	12	0.5 ms

Table 3-3: Numerologies supported in typical NR systems

3.2.1.2 Bandwidth Structure

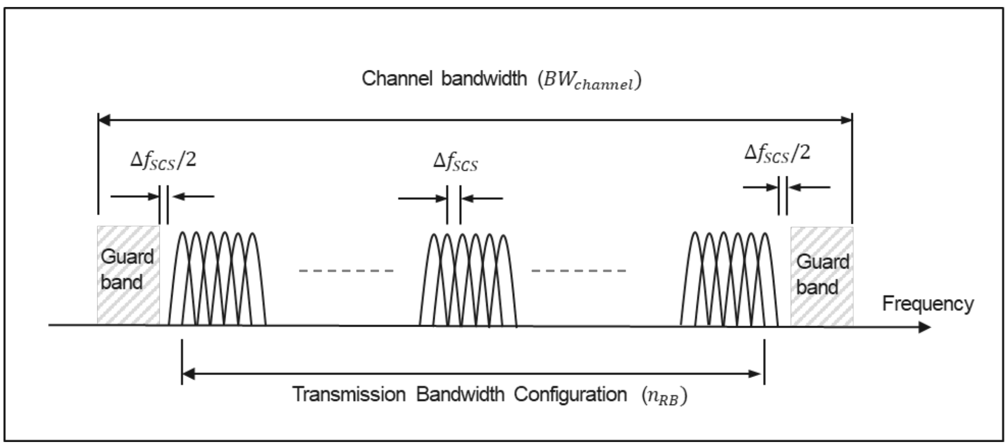


Figure 3-1: Channel bandwidth and transmission bandwidth configuration. From [1, p. 351] .

3.2.1.3 System model

Figure 3-2 shows a generic system model for FRMCS using a radio modem mounted inside the train and an external antenna mounted on the roof of the train. Various parameters that are used for a link budget are shown.

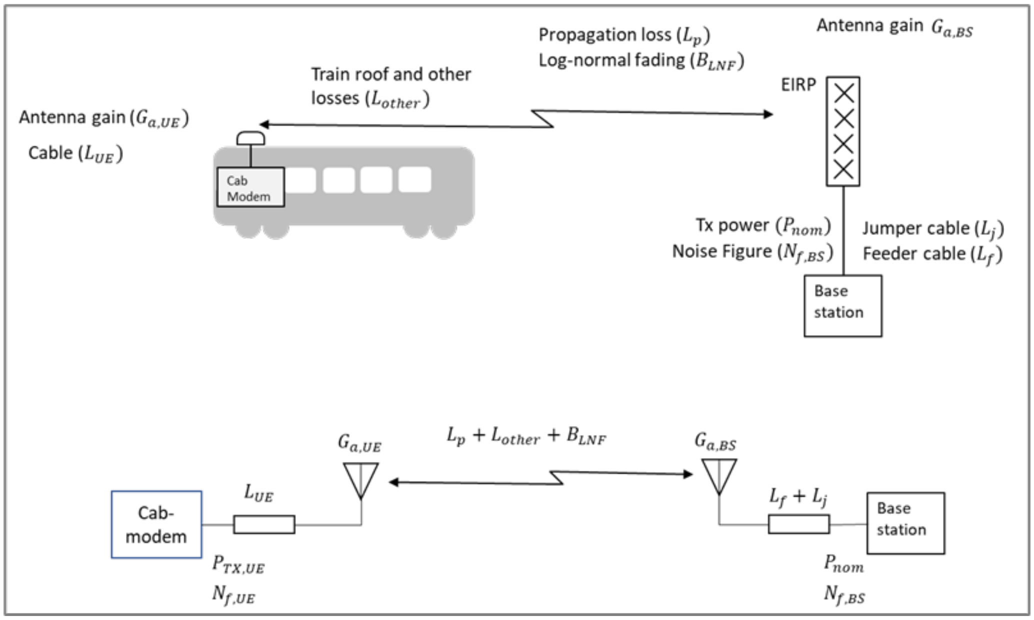


Figure 3-2: System model for FRMCS modem link budgets

3.2.1.4 BS and UE antenna configuration and transmission path

A transmission path configuration is specified using the notation nT-mR where n is the number of transmitters and m is the number of receivers. This determines the maximum MIMO layers and the choice of link curve used in the link budget. The maximum MIMO layers that can be supported is given by:

$$n_{layers,max} = \min(n,m)$$

This is illustrated in Figure 3-3 for BS configuration 4T4R and UE configuration 1T2R. In this case, the DL and UL transmission paths are described as 4T-2R and 1T-4R respectively. The maximum number of downlink MIMO layers is min (4,2) = 2.

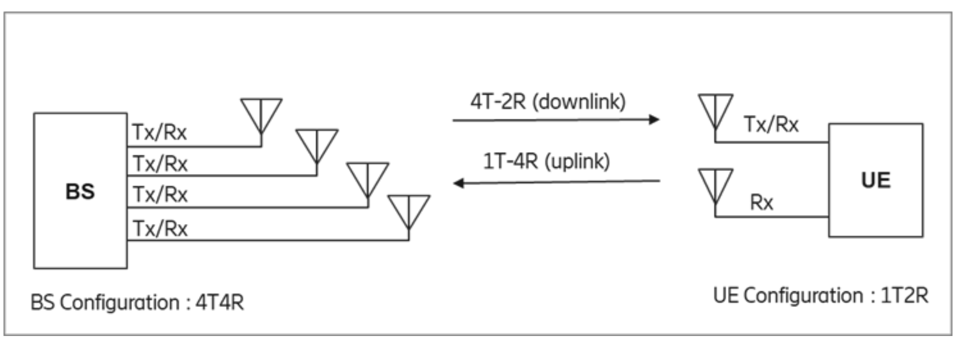


Figure 3-3: Notation for transmission paths and BS and UE antenna configurations

3.2.1.5 FRMCS Track Segment Model

The following figure shows a model for a track segment. FRMCS BS sites are assumed to be providing coverage up and down the track using two cells (sectors). Other configurations are also possible, for example using RF splitting of a signal between antennas on a site.

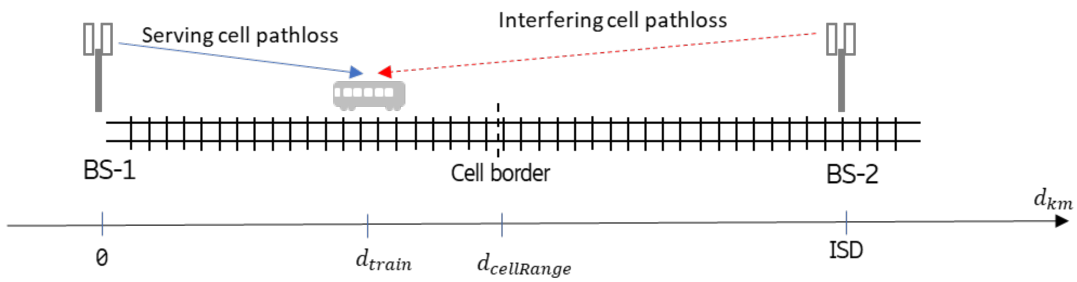


Figure 3-4: FRMCS track segment model

3.2.2 RF coverage levels for FRMCS

3.2.2.1 Link Budget

A link budget for NR can be constructed for uplink and downlink with main objective to establish the maximum pathloss such that uplink and/or downlink bitrate targets can be met for a UE at the cell border. Key parameters to be considered are:

- Total BS transmit power
- System bandwidth and maximum resource blocks
- UE and BS receiver noise figures
- UE and BS antenna gains
- UE and BS Tx and Rx antenna configurations (e.g. 2T2R or 4T4R).
- BS and UE cable losses
- Other losses
- Interference from other-cell BS (downlink) and UEs (uplink)

The methodology usually adopted is to calculate **the *achievable* UL and DL bitrates for a UE on a serving cell and located at the *cell-edge*** (border). This assumes a single UE is in the serving cell using all available resources. The cell edge bitrate targets therefore must consider not just the single user bitrate requirement, but also the number of UEs in the cell. Once link budget parameters have been selected, an iterative methodology is used to determine the maximum pathloss that can support the required UL and DL cell-edge bitrates.

Usually, NR link budgets are calculated per resource block. For example, a total BS transmit power of 46 dBm using 25 RBs would transmit 46-10 $\log_{10}(25)$ dBm/RB= 32 dBm per RB. Similarly, the thermal noise level at a receiver with a noise figure F_UE [dB] and using a RB bandwidth of 180 kHz, is given by:

$$N_{th,RB} = -174+F_{UE}+10\times\log_{10}(180{,}000)\ [\text{dBm}].$$

3.2.2.2 Mapping of SINR to bitrate

Mapping of SINR to bitrate is required and this relies on link curves obtained from simulation or measurements. These link curves take into account the following main parameters:

- Radio channel multipath profile (e.g., 3GPP TDL-A or TDL-C channels)
- UE speed
- Carrier frequency and bandwidth
- BS and UE antenna configurations
- Transmission configuration

In general, performance can be expected to degrade with increasing UE speed. Increasing the number of Rx antennas improves coverage and can also allow the use of high order MIMO.

Figure 3-5 shows an example of link curves for 2Tx and 4Tx base stations with 2Rx UE receivers. The beamforming gain due to 4Tx is seen.

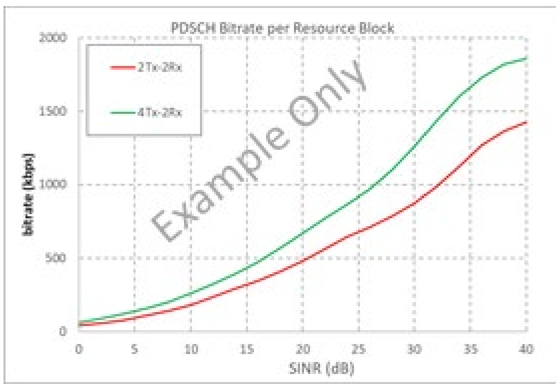


Figure 3-5: Example downlink link curve for PDSCH, including overheads.
15 kHz subcarrier spacing

Figure 3-6 shows an example of link curves for the uplink. Using 4Rx in the base station results in a diversity gain of approximately 3 to 4 dB. Using 2Tx in the UE results in higher bitrates due to spatial multiplexing where 2-MIMO layers are used at >7 dB SINR.

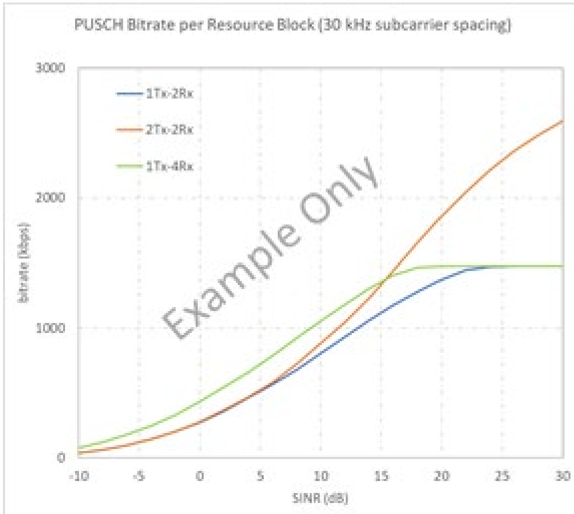


Figure 3-6: Example uplink link curves for PUSCH, including overheads.
30 kHz subcarrier spacing

The general form of the SINR to bitrate mapping is:

The general form of the bitrate calculation is:

$R_{\gamma=} n_{RB} \times R_{linkCurve,RB} (\gamma) \times k_{tdd} \times (1-k_{OH})$

Where:

n_{RB} is the number of resource blocks

k_{tdd} is the TDD fraction for the UL or DL. For FDD, k_tdd = 1.0

k_{OH} is the OH fraction

$R_{linkCurve,RB} (\gamma)$ is the link curve bitrate per resource block

For the downlink, all RBs are assumed to be used to calculate the achievable bitrate. For the uplink, the required RBs for optimal bitrate can be derived. For low bitrates and large pathloss, the number of UL RBs may be reduced to maintain a minimum SINR per RB (typically -3 dB) to ensure correct demodulation.

3.2.2.3 Overheads

Overheads are accounted for separately for the UL and DL. For the DL, overheads include:

- SSB
- PDCCH
- DMRS transmitted on PDSCH resource blocks
- CSI-RS used for channel estimation

For the uplink, overheads include:

- Sounding Reference Signal (SRS) in TDD
- PDCCH resource blocks
- PRACH resource blocks
- DMRS transmitted on PUCCH resource blocks

3.2.2.4 Log-normal Fading

Log-normal fading is handled through a LNF fading margin.

Large scale fading is a process that affects signal levels associated with the clutter around a UE. It is a statistical process and is modelled using a normal distribution of the received signal power in logarithmic units (i.e., dBs). It is commonly called Slow Fading or Log-Normal Fading (LNF).

The key parameters that are used to derive B_LNF is the coverage reliability over the cell area (typically 95%), and the standard deviation (σ_{LNF}) of the LNF process (typically 6 to 12 dB). By using analytical methods it is also possible to estimate the reliability of the user moving along the cell border.

This is illustrated in Figure 3-7 for a UE moving along the notional cell border. The received signal and interference levels are subject to LNF resulting in fluctuating bitrate. In this example, the cell edge bitrate ($R_{cellEdge}$) is chosen such that there is a 95% probability (area reliability) that $R>R_{cellEdge}$ when averaged over the cell area. Along the cell border the reliability is 70%.

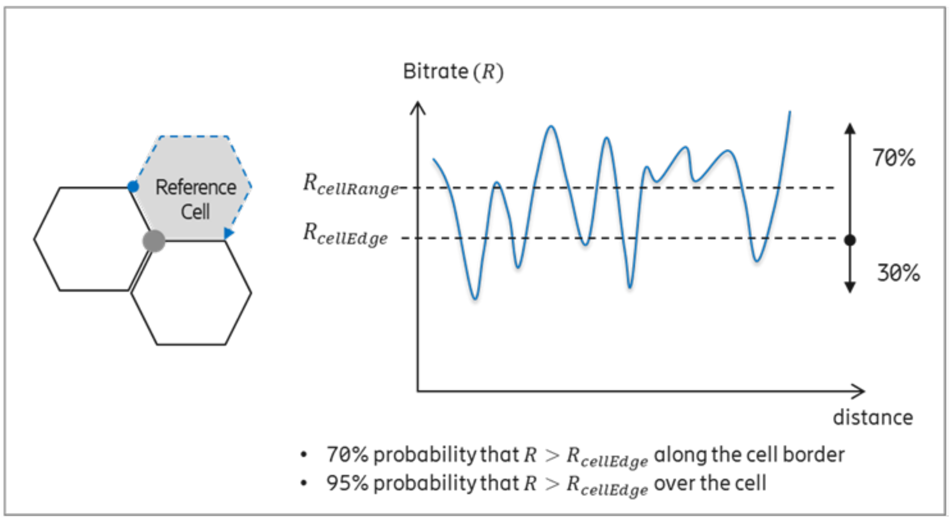


Figure 3-7. Example of cell edge throughput reliability

In coverage link budgets, an LNF margin (B_{LNF}) is added to the received signal power attenuation in link budget calculations. This can be derived analytically or using simulations. Analytical methods have some limitations, so simulation is used to help overcoming the limitations.

LNF margins may also include macro-diversity (hard-handover) gains. In general, analytical methods do not include these, and they must be considered as a separate item in the link budget. Simulation based LNF margins on the other hand, can include macro-diversity gains.

3.2.2.5 LNF margins for Rail applications:

Large scale fading for rail FRMCS applications is expected to have quite different characteristics to that of handheld users in a cellular network and the simulation and analytical methods may not be suited. In particular:

- Fading between wanted and interfering sources may be highly correlated (e.g., a train in a short tunnel).
- Trains moving at higher speeds will move quickly through fades, and a LNF margin may not be required.
- The site layout for FRMCS is normally more linear[7] than a homogeneous cell plan (i.e., with a hexagonal grid).
- Propagation channels may be more line-of-sight than for cellular networks, resulting in lower LNF margins.
- Fading may not be log-normally distributed, especially in line-of-sight conditions.

3.2.2.6 TDD

TDD is modelled by calculating the fraction of slots used for UL and DL transmissions.

As an illustration, figure 3-8 below shows a proposed FRMCS 1900 MHz TDD pattern. An example of how TDD fraction can be calculated is shown below:

There are 14×10=140 OFDM symbols intervals per pattern period. In the pattern period, the UL and DL TDD fractions are:

$k_{TDD,DL}$ =(4×14 +6+10)/140 = 51.4%

$k_{TDD,UL}$ =(4×14+4)/140 = 42.8%

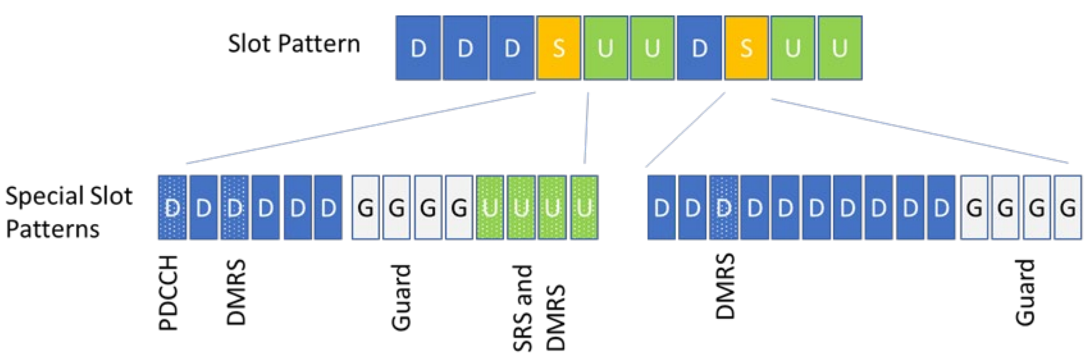


Figure 3-8: TDD pattern for proposed FRMCS pattern DDDSUUDSUU (10:4:4, 10:4:0). Subcarrier spacing 30 kHz. DL and UL only slots may contain 1, 2 or 3 DMRS symbols

[7] Except for railway stations and shunting yards this can be hexagonal.

3.2.2.7 Intra System Interference Modelling

Interference in NR is due to loading on other-cells (downlink) and UEs transmitting on other cells.

Interference is handled using an interference margin added to the SINR. This can be estimated analytically for a certain cell plan (geometry). For FRMCS linear track segment, a good assumption to use is that the total DL interference power at the cell edge UE is equal to the received signal power. The DL interference margin also takes into account the effective DL loading (or resource utilisation) on the other cell. For FRMCS this will usually be small due to minimum required train spacing.

Uplink interference is more difficult to model analytically as it depends on a number of factors such as UE location. Based on simulations and field experiences for eMBB, uplink interference margins in the order of 1 to 2 dB could be suitable for FRMCS applications.

Interference margins are applied in SINR calculations for both uplink and downlink. The general form for calculating a wanted signal to interference plus thermal noise ratio (SINR) is:

$$SINR = \frac{P_{signal}}{N_{therma}+P_{interference}}$$

This calculation is performed using linear units. To facilitate calculations using decibels, P_interference can be expressed as a multiple of the thermal noise N_th (in liner units):

$$SINR = \frac{P_{signal}}{N_{thermal}B_{IM}}$$

where the interference margin is given by (in linear units):

$$B_{IM} = 1 + \frac{P_{interference}}{N_{thermal}}$$

Once B_IM is calculated, SINR can now be calculated (in dBs) as:

$$SINR = P_{signal} - N_{thermal} - B_{IM} \quad \text{[dB]}$$

3.2.2.8 Example of mapping voice services to the physical layer of the FRMCS air interface

The transmission of speech results in different data rates on the **physical layer of the FRMCS air interface** due to the use of adaptive codecs (like EVS 24.4 codec), usage of special functions (like Voice Activity Detection, compression rate, voice payload size and voice packets per second) and the mapping of the variable voice payload into IP packets.

In an NR system, *data services* typically use a block error rate (BLER) of around 10%. Selective retransmissions can be used to result in a lower error rate, typically in the order of 1%. The use of retransmissions results in an optimal balance between coverage and capacity. Usually, data service bitrates for a UE can be added to obtain an aggregate bit rate which is then mapped to a required SINR using a *link curve* and used in a link budget to estimate coverage.

It is not correct to simply add the voice and data service bit rates to obtain an aggregate bitrate. This is because data and voice services operate with different BLER requirements, and the link curves will be different. Retransmissions of speech frames cannot be relied upon since this adds to speech delay. Frame Erasure Rates (FER) for acceptable speech quality are typically 1%.

For voice services, the following must also be considered:

1. The voice codec rate.
2. IP and RAN header overheads, allowing for Header Compression if used.

In order to estimate an aggregate bitrate for dimensioning, one approach is to add a margin to data service SINR values – this can be based on simulations or measurements and use this to obtain the *equivalent* data service bit rate for voice, see figure 3-9 below. This then allows data rates for data and voice services to be added together and coverage to be estimated based on a data link curve.

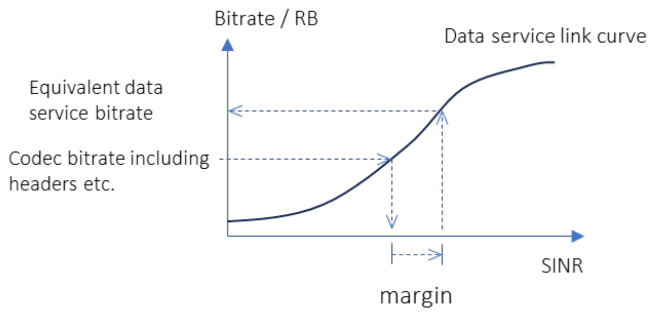


Figure 3-9: Data service link curve

An example of how aggregate data bit rates can be calculated is shown in the following table for an EVS24.4 codec using Robust Header Compression (RoHC) to reduce IP overheads.

	Voice Codec	EVS 24.4	
	Codec Rate	24.4 kbps	
	IP and RAN header overhead bit rate using Robust header compression (RoHC)	6.6 kbps	Typical value, can be higher
	Total codec plus IP and RAN header overheads bitrate	31 kbps	Without RoHC the datarate is 45 kbps
a	Equivalent eMBB uplink data rate for voice (1% FER)	65 kbps	From data service link curve (uplink). A margin of 6 dB is estimated from fast fading margin (12 dB) and feature gains (6 dB), for example VoNR frequency hopping. Note: FFS
b	ATO Data link	20 kbps	
c	ETCS Data link	10 kbps	
d	Aggregate bitrate for dimensioning	95 kbps	=a+b+c

Table 3-3: Example Calculation of Aggregate Bitrate

Note that this is an example to illustrate the concept of obtaining an aggregate bitrate. Values may be different depending on IP and RAN header overheads, base station TxRx configuration, train speed (affecting fast fading margins), network voice features (for example frequency hopping (FH) and link adaptation settings). FH is part of VoNR and VoLTE. It means that RBs are changed constantly and only use 2 RBs for voice.

3.2.2.9 Cell Edge Bitrates and Cell Throughput

Cell edge throughput is usually used for dimensioning a maximum allowable pathloss to meet a minimum required throughput (R_{min}). Usually, all cell resources[8] are assumed to be available for the theoretical cell edge user and therefore no other users can be accommodated. Therefore, it is usually necessary to increase R_{min} to accommodate other users in the cell.

The cell throughput is the aggregate of bitrates for all users in a cell. Placing users in good radio conditions (high SINR) will result in each user being served faster (assuming users have a fixed data packet size) and the load contribution per user (resource utilisation) will be lower. Conversely, if all users are at cell edge, the load contribution per user will be higher. The total cell load will be the sum of individual user load contributions. For a given maximum load (for example 75%), the total load will be a function of the number of trains, train locations and their respective radio conditions.

In the FRMCS scenario, the aggregate bitrate per train multiplied by the expected "worst case" number of trains at the cell edge can be used as a starting point for dimensioning. Typically, FRMCS will be required to serve one or two trains in cell edge conditions (high load contribution), plus a number of other trains distributed throughout the cell in better radio conditions and with a lower load contribution.

3.2.2.10 Example Link Budget (900 MHz FDD with 5 MHz bandwidth).

This example link budget for FRMCS-900 (5 MHz) assumes a linear track side deployment. The required aggregate[9] cell edge uplink bit rate target is given as 858 kbps and the objective of the link budget is to ensure that this criterion is met or exceeded. The downlink requirement is ≥ 975 kbps.

Note: This link budget should not be taken as representative of an actual deployment. It is intended to illustrate the concepts and form of NR link budgets.

The DL loading has been set to 25%, UL loading margin set to 1 dB (assumed). A mast mounted remote radio has been assumed with 0.3 dB jumper loss to the 18 dBi antenna. The BS config is 2T2R, and UE is 1T2R with 31 dBm UE Tx power. The UE Noise figure is 7 dB and the UE antenna gain is 0 dBi with 6 dB cable loss.

Solving for the limiting link results in the following link budget. Note that in this case, the UL is the limiting link with the DL (4,214 kbps) exceeding the required target of 975 kbps. To achieve the uplink bitrate target, an average of 19.7 resource blocks are used.

[8] An exception is for the uplink where the number of RBs per user is low (low data rate) and multiple users can be served at the same time, each using separate RBs.

[9] Aggregated over several trains, and also multiple services of data and voice. To a first approximation, this will be modelled as single UE at the cell edge, requiring the aggregate bitrate.

	PUSCH	PDSCH	
UE Tx Output Power	31.0 dBm	46.0 dBm	BS Tx Power/ Carrier
PUSCH Resource Blocks	19.7	25.0	PDSCH Resource Blocks
Tx power per Resource Block	18.0 dBm / RB	32.0 dBm / RB	Tx power per Resource Block
Resource Block Bandwidth	180 kHz	180 kHz	Resource Block Bandwidth
PUSCH Bitrate	867 kbps	4,214 kbps	PDSCH Bitrate
Thermal Noise per RB	-118.4 dBm	-114.4 dBm	Thermal Noise per RB
SINR	-3.0 dB	4.2 dB	SINR
Sensitivity per RB	-121.4 dBm	-110.3 dBm	Sensitivity per RB
Rx Power	-120.4 dBm / RB	-100.5 dBm / RB	Rx Power
UE Antenna Gain	0.0 dBi	0.0 dBi	UE Antenna Gain
BS Antenna Gain	18.0 dBi	18.0 dBi	BS Antenna Gain
BS losses (UL)	0.3 dB	0.3 dB	BS Losses (DL)
UE Losses	6.0 dB	6.0 dB	UE Losses
Foliage Loss	0.0 dB	0.0 dB	Foliage Loss
Train Roof Losses	0.0 dB	0.0 dB	Train Roof Losses
Total Common Losses	0.0 dB	0.0 dB	Total Common Losses
LNF Margin	5.6 dB	5.6 dB	LNF Margin
Interference Margin	1.0 dB	3.8 dB	Interference Margin
Pathloss	144.7 dB	144.7 dB	Pathloss
Signal Attenuation / Coupling Loss	138.5 dB	138.5 dB	Signal Attenuation / Coupling Loss

Table 3-4: 900 MHz Example Link Budget FDD with 5 MHz Bandwidth

Comment on Link Balance
The concept of link balance is not widely used for NR dimensioning. Rather the focus is on meeting or exceeding required cell edge bitrate targets for UL and DL. In this example, reducing the downlink transmit power could be used to make the DL bitrate equal to the UL bit rate. However, this will also reduce the cell downlink capacity and is not recommended.

3.2.2.11 Example Link Budget (1900 MHz TDD with 10 MHz bandwidth)

Next a similar scenario is considered for TDD using a DDDSUUDSUU TDD pattern and operating with 10 MHz bandwidth at 1900 MHz. The uplink and downlink cell edge bit rate requirements are given as 728 kbps and 845 kbps respectively. The link budget below shows that the uplink is the limiting link with the target being met (735 kbps). The downlink target achieved bitrate is 2,979 kbps.

Note that the pathloss is reduced by 2.7 dB from 144.7 dB (FDD at 900 MHz) to 141 dB. This is mainly due mainly to the impact of 40% of slots being used for uplink.

N1900/ 10 MHz (TDD)

	PUSCH	PDSCH	
UE Tx Output Power	31.0 dBm	46.0 dBm	BS Tx Power/ Carrier
PUSCH Resource Blocks	20.5	24.0	PDSCH Resource Blocks
Tx power per Resource Block	17.9 dBm / RB	32.2 dBm / RB	Tx power per Resource Block
Resource Block Bandwidth	360 kHz	360 kHz	Resource Block Bandwidth
PUSCH Bitrate	735 kbps	2,979 kbps	PDSCH Bitrate
Thermal Noise per RB	-115.4 dBm	-111.4 dBm	Thermal Noise per RB
SINR	-2.5 dB	4.5 dB	SINR
Sensitivity per RB	-117.9 dBm	-106.9 dBm	Sensitivity per RB
Rx Power	-116.9 dBm / RB	-96.6 dBm / RB	Rx Power
UE Antenna Gain	0.0 dBi	0.0 dBi	UE Antenna Gain
BS Antenna Gain	18.0 dBi	18.0 dBi	BS Antenna Gain
BS losses (UL)	0.3 dB	0.3 dB	BS Losses (DL)
UE Losses	6.0 dB	6.0 dB	UE Losses
Foliage Loss	0.0 dB	0.0 dB	Foliage Loss
Train Roof Losses	0.0 dB	0.0 dB	Train Roof Losses
Total Common Losses	0.0 dB	0.0 dB	Total Common Losses
LNF Margin	5.6 dB	5.6 dB	LNF Margin
Interference Margin	1.0 dB	4.4 dB	Interference Margin
Pathloss	141.0 dB	141.0 dB	Pathloss
Signal Attenuation / Coupling Loss	134.8 dB	134.8 dB	Signal Attenuation / Coupling Loss

Table 3-5: 1900 MHz Example Link Budget FDD with 10 MHz Bandwidth

3.2.2.12 Use of Link Budget Outputs

The main output of a link budget is the maximum pathloss at which both UL and DL bitrate requirements are met and the associated SINR per Resource block. For the uplink it is also important to note the number of resource blocks used. For the DL, SINR[10] is a quantity that can be measured by UEs. For the uplink, SINR is usually not a suitable quantity to easily measure - downlink RSRP (based on BCH) can be used as a proxy as follows:

Use the link budget to calculate the maximum pathloss and the maximum signal attenuation $L_{sa,max}$ (between Tx and Rx reference points). The RSRP can be calculated from the reference signal transmit power (per resource element):

$$RSRP = P_{Tx,RS} - L_{sa,max} \quad \text{[dBm]}$$

$$P_{Tx,RS} = P_{Tx,RB} - 10 \times \log_{10}(n_{RB} \times 12) \quad \text{dBm}$$

Note that RSRP threshold is dependent on link budget parameters agreeing with those in the real network or in the RF planning tool, including downlink transmit power, SSB configuration, system bandwidth etc.

[10] Strictly speaking, the SINR in the link budget is the PDSCH SINR. This will be different to the BCH or SSB SINR which has 100% loading.

For radio planning tools applications, it is common practice to calculate the downlink SINR for an assumed other-cell loading (e.g., 25%). This can then be mapped to downlink bitrates.

For the uplink, an uplink bitrate threshold (e.g., 1.2 Mbps) can be calculated using a link budget and then the associated RSRP calculated. Coverage maps can then be produced.

The use of RSRP for downlink planning is not recommended.

3.2.2.13 Use of Link Budget Outputs

The main output of a link budget is the maximum pathloss at which both UL and DL bitrate requirements are met and the associated SINR per Resource block. For the uplink it is also important to note the number of resource blocks used. For the DL, SINR[11] is a quantity that can be measured by UEs. For the uplink, SINR is usually not a suitable quantity to easily measure - downlink RSRP (based on SSB) can be used as a proxy as follows:

Use the link budget to calculate the maximum pathloss and the maximum signal attenuation $L_{sa,max}$ (between Tx and Rx reference points). The RSRP can be calculated from the reference signal transmit power (per resource element):

$$RSRP = P_{Tx,RS} - L_{sa,max} \qquad \text{[dBm]}$$
$$P_{Tx,RS} = P_{Tx,RB} - 10 \times \log_{10}(n_{RB} \times 12) \quad \text{dBm}$$

Note that RSRP threshold depends on link budget parameters agreeing with those in the real network or in the RF planning tool, including downlink transmit power, SSB configuration, system bandwidth etc.

For radio planning tools applications, it is common practice to calculate the downlink SINR by assumed cell loading for other cell (e.g. 25%). This can then be mapped to downlink bitrates.

For the uplink, an uplink bitrate threshold (e.g. 1.2 Mbps) can be calculated using a link budget and then the associated RSRP calculated. Coverage maps can then be produced.

The use of only RSRP for downlink planning is not recommended.

3.2.3 Impact of external interferences

Any FRMCS radio network will be subject to external interference. At least the adjacent MNO 2G/4G/5G bands 8/n8 and 1/n1 will create unwanted emissions that fall in the FRMCS BS and UE receive bandwidths. There may also be other sources of external interferences.

An estimation of this interference level may be obtained on a theoretical basis from the 3GPP specifications for 2G/4G/5G Base stations and UEs. This is FFS.

Additionally, it is expected that the MORANE2 tests will provide a view on the level of external interferences that may be expected in bands n100 and n101.

[11] Strictly speaking, the SINR in the link budget is the PDSCH SINR. This will be different to the BCH or SSB SINR which has 100% loading.

3.2.4 RB allocation in the Uplink

Both for TDD and FDD there may be benefit in using a limited number of RBs at cell edge to maximize the available transmit power for that RB to achieve better coverage / higher SINR than if multiple RBs would be used. Details of RB allocation is vendor specific due to the fact that the scheduler is not specified by 3GPP.

3.2.5 MIMO and diversity operation

Advanced multi-antenna radio technologies are promising elements to achieve higher data rates, to optimise robustness and increase cell range in communication networks. Different MIMO-technologies provide different benefit aspects as UL versus DL, one UE versus multiple UEs in a cell, enhance coverage versus throughput.

FRMCS use cases and requirements are different to public networks, especially in these aspects: higher availability, more focus on uplink, and may also evolve to have to support higher data throughputs (e.g., for high video bandwidth necessary for GOA 4). An overview on MIMO and Beamforming technologies and their technical background may be found in: [Ref18]

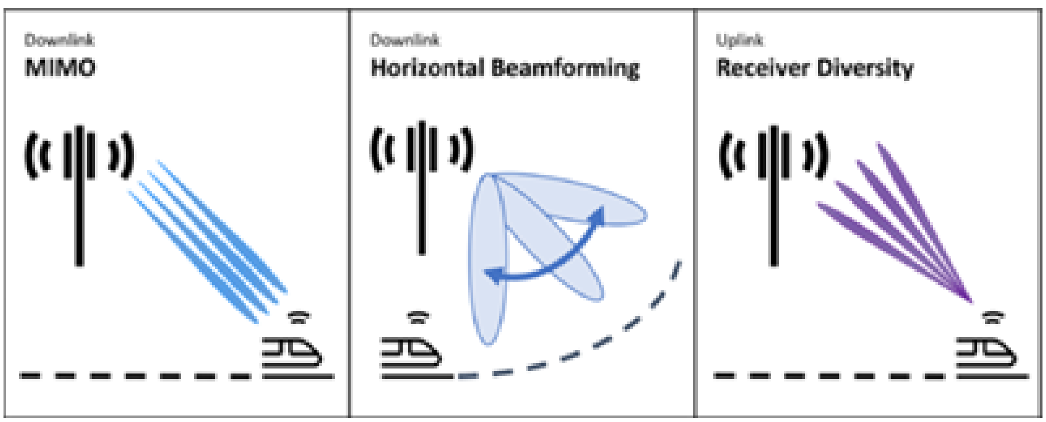


Figure: 3-10: Multi-antenna technologies

3.2.5.1 MIMO at the BS site

In public mobile networks on the BS side, both active or passive antenna systems can be used for 5G.

From a physical implementation perspective, active and passive antenna systems are defined as follows:

- An active antenna system (AAS) contains an antenna-integrated radio unit that feeds the passive antenna array to optimise capacity and coverage. The integrated unit combines the antenna, radio, tower mounted amplifier, feeder, and jumper functionalities into one single unit.
- In passive antenna systems (non-Active Antenna System; non-AAS) the antennas and radio units are located in different hardware modules. 5G standards support passive antenna systems with up to 8 antennas (8T8R).

It should be recalled that the coexistence studies performed by CEPT, and hence ECC Decision (20)02 and EU Decision 2021/1730, only consider non-AAS systems for FRMCS. CEPT/ECC has provided the following definitions for AAS and Non-AAS:

- *AAS (Active Antenna Systems) refers to MNO base stations and antenna systems where the amplitude and/or phase from the various antenna elements is continually adjusted resulting in an antenna pattern that varies in response to short term changes in the radio environment. This is intended to exclude long term* beam shaping such as fixed electrical down tilt.
- *Non-AAS (non-active antenna systems) refers to MNO base stations that provide one or more antenna connectors, which are connected to one or more separately designed passive antenna elements to radiate radio waves. The amplitude and phase of the signals to the antenna elements is not continually adjusted in response to short term changes in the radio environment.*

The following technologies are applicable to non-AAS antennas:

Diversity at the transmitter or receiver site enhances signal quality and therefore also leads to a gain in coverage. There are different combining methods such as Maximum Ratio Combining (MRC) and Interference Rejection Combining (IRC). Coherent combining in general concerns the ability of a receiver to combine in phase the signals received through several channels. This type of feature has been implemented since the early days of mobile communications, as it combats the deep fading observed in mobile channels. When the receiving antennas are sufficiently spaced, the channels become decorrelated, and the power of the signal received after coherent combination becomes more stable, thus increasing link quality.

Coherent combining can also be envisaged in the context of several geographically separated base stations where it leads to coordinated multi-point operation (see also section 3.2.6). In DL, it is up to the base stations to ensure that the received signals arrive in phase at the terminals. This is known as coherent joint transmission (CJT). A similar principle also exists in UL, where the base stations work together to combine the signals they receive. This is known as Uplink Coordinated Multipoint (Uplink CoMP).

Single-User MIMO allows spatial multiplexing which helps enhancing cell capacity and throughput. The MIMO-algorithms in combination with decorrelated transmission paths allow multiple usage of the same time-/frequency-resources. There are two different types: Closed Loop (CL) and Open Loop (OL) spatial multiplexing. CL spatial multiplexing works with a feedback loop between UE and BS and is therefore mostly working in moderate and low speed scenarios. OL spatial multiplexing should also work in high-speed scenarios. Multi-antenna field trials conducted in the '*Erzgebirge*' further analysed this topic [Ref 25] but due to restricted velocities of max. 50km/h no significant difference between OL and CL could be seen. Further analysis with high speed UEs would be interesting.

Beamforming is a general term to designate the capability of a multiple antenna transmitter in a base station or in a user device to focus the energy into specific directions. This is achieved by controlling the phases and possibly the amplitudes of the signals emitted by each antenna. It can be verified that when these antennas are spaced by a fraction of a wavelength (typically half), the signals perceived in the far field are focused in specific directions. It is thus possible to illuminate certain parts of the cell selectively in the direction of the intended users. Beamforming is only working in the horizontal plane for non-AAS antennas.

3.2.5.2 MIMO/Diversity operation to enhance the uplink

In a LTE network at 1900 MHz [Ref 23] **UL Rx diversity** has been tested in a single-input multiple output (SIMO) configuration. The system has been configured that data is transmitted from one Tx antenna port on the train and multiple copies of the same data are received across independently fading channels at up to N Rx antenna ports on trackside. This increases a chance of properly receiving the transmitted data which improves transmission robustness and, in consequence, capacity and coverage, both in terms of cell size and application coverage.

In the field trials, up to N=8 receivers have been studied. UL Rx diversity improves user throughput directly in uplink but it can indirectly improve in downlink as well. The improvement in throughput is generally available for all users in the whole cell but the effect is greater at the cell edge. More antenna ports and additional diversity extend the reach of the uplink by improving the resilience to fading e.g., the coverage enhancements of 4-way and 8-way in comparison to 2-way Rx diversity can be in the order of 3 dB and 6 dB, respectively.

The following figures show the results of the trial:

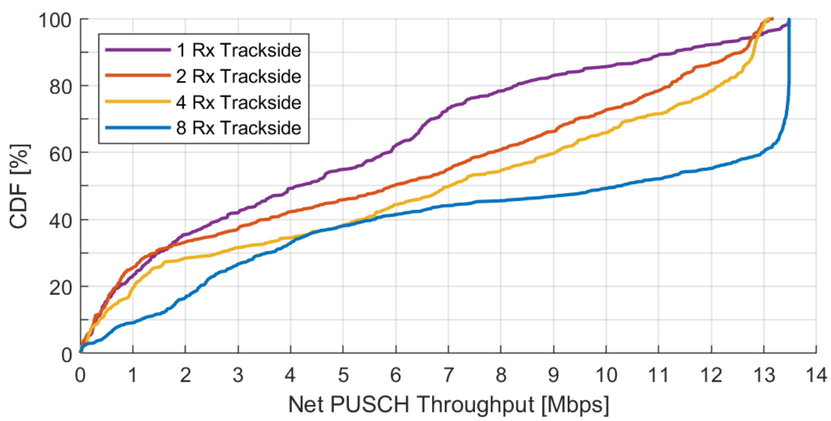


Figure: 3-11: Uplink performance of different trackside antenna configurations with Rx diversity, measured along the overall test track

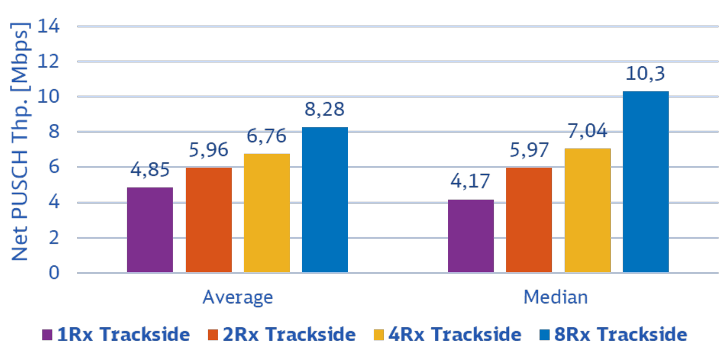


Figure: 3-12: Average and median uplink throughput with Rx diversity for the overall test track

3.2.5.3 MIMO at the UE side

By using multiple Rx antennas at the UE side improvement in the DL may be obtained.

The following table shows a summary of the simulations and measurement results that took place with different MIMO-technologies at the UE side.

MIMO technologies:	**Channel:**	**Benefit:**	**Analysis based on:**
Rx Diversity gain in downlink	Should work everywhere	• Slightly Throughput (due to addition of input power) • Mainly Coverage (DL) • Availability (DL)	<u>Simulations:</u> ETSI TR 103 554-2 V1.1.1 (2021-02)
MIMO Mx[12] Gain (open loop in downlink)	• High speed/medium speed/low speed • Surrounding (urban+/rural?) • Polarization div can help	• Throughput (DL/Cell) • Coverage (DL) • Availability (DL) • Reliability	<u>Simulations:</u> ETSI TR 103 554-2 V1.1.1 (2021-02) <u>Field trial results (LTE):</u> Field Study on Multi-Antenna Radio Technologies for Future Railway Communications at 1.9 GHz: • Measurements in Erzgebirge: medium/low speed, rural, hilly terrain • 2Rx: open loop • 4Rx: open loop/closed loop <u>Open issues for downlink performance:</u> • Closed loop vs. Open loop performance at high speed • Gain of 4 vs. 2 Rx antennas at high speed
MIMO Mx Gain (closed loop in downlink)	• Medium speed/low speed • Surrounding (urban+/rural?) • Polarization div		

Table 3-6: Comparison MIMO technologies

[12] Mx Gain is the increase in bandwidth efficiency by transmit signal processing and channel coding aiming at the parallel transmission of independent information streams at the same time inside the same bandwidth.

The following figures show the measurements results with different numbers of antennas at the UE-side on the downlink performance, as taken from [Ref 23]. The DL MIMO test configurations included up to 4x4 in TM3 and up to 8x4 in TM9, including digital horizontal beamforming on transmission time interval (TTI) level in TM9. Note that all these DB measurements took place in a hilly region at low velocity (max. 50km/h).

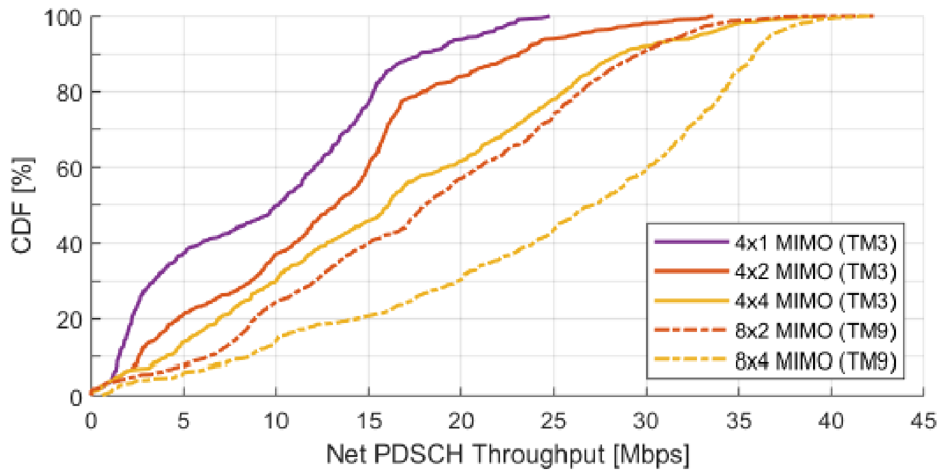


Figure 3-13: Downlink performance of TM3 (MIMO) and TM9 (MIMO & beamforming) configurations, measured along the overall test track

DL MIMO Configuration	4x1 TM3	4x2 TM3	4x4 TM3	8x2 TM9	8x4 TM9
Avg. PDSCH Throughput [Mbps]	*9.4*	*12.7*	*16.4*	*17.9*	*24.5*

Table 3-7: Average downlink throughput for the overall test track

The above Figure 3-13 shows the cumulative distribution of the DL throughput for 4x1, 4x2 and 4x4 MIMO inTM3 as well as 8x2 and 8x4 MIMO in TM9. As expected, the MIMO gain increases when increasing number of Rx at the on-board antenna. The average gain is approximately 30% for both 4x2 vs. 4x1 and 4x4 vs. 4x2 in TM3, given the multipath propagation conditions of the studied rural setup. Figure 3-11 depicts the statistical evaluation of the rank of the channel matrix which is an indicator of how many parallel data streams can be spatially multiplexed over the air. Apart from the rank the used channel coding will define the actual performance. Higher rank and higher modulation and coding are the main contributor to the DL performance increase for the different MIMO configurations. The use of TM9 with higher Tx number and beamforming gain provide a strong DL throughput gain as compared to TM3 in our setup, also being reflected in higher rank usage. The average gain is approximately 50% for 8x4 vs. 4x4 and 40% for 8x2 vs. 4x2.

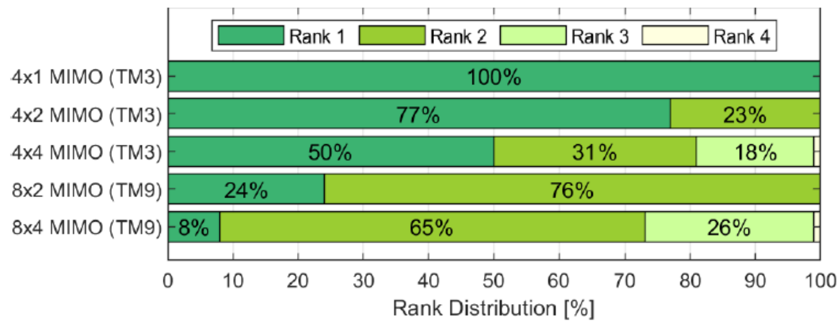


Figure 3-14: Measured rank for the downlink network configurations

It could be assumed that the downlink throughput and MIMO rank in the Downlink could be significantly enhanced by using more antennas at the UE-Rx side.

As stated above, in FRMCS the Uplink is the limiting factor. More Rx antennas at UE side (e.g. 4 instead of 2) will not enhance uplink performance as n100/n101 do not include uplink MIMO in 3GPP Release 18 5G UEs. So independent of the number of antennas connected only one will be used for Tx.

Uplink MIMO has been simulated in ETSI TR 103 554-2 V1.1.1 (2021-02) which demonstrated that the gains from transmit diversity with more transmitters at the UE side were limited. This is because the maximum Tx power in the UL-MIMO case has to be divided between both Tx paths as the maximum allowed EIRP is limited by regulation.

In the current FRMCS spectrum regulation (see ECC Report 313 - table 4 & ECC Report 314 - table 5), the on-board UE is allowed a maximum of 33 dBm EIRP (i.e. 31 dBm UE output power, + 5 dBi antenna gain and -3 dB hardware losses). From track side implementation perspective, it is advantageous to create the highest possible EIRP level. Unfortunately, due to cable losses and train integration reasons (see section 4.2.1.1 for more details), the expected maximum EIRP is only 25 dBm. Because the FRMCS system is uplink limited, any gains in uplink performance will greatly help improving system performance. Further interaction with industry and FRMCS projects are ongoing with the goal to achieve an EIRP level as close as possible to the regulatory maximum allowed 33 dBm.

The above results suggest that at least 2 Rx antenna diversity should be used at the UE side. This is in line with the 3GPP specification 3GPP TS 38.101 that a minimum of two Rx antennas is necessary for 5G UEs. Therefore, the required minimum setup for the FRMCS on-board is 2 antennas (1: Tx/Rx, 2: Rx)

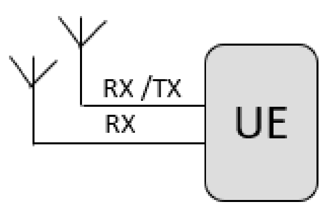


Figure 3-15: UE antenna configuration

If additional Rx filters external to the radio module are needed, more Rx antennas also mean more filters. Depending on the filter type this may result in a lot of weight and space needed when applying more Rx antennas.

Uplink MIMO might be further evaluated for its benefit to enhance reliability by making use of Tx diversity. In combination with cross-polarised train-antennas a significant multiplex gain could also be expected and might be worth to further analyse.

For installations where higher downlink bandwidth is required 4 Rx antennas might be useful. Open issues on benefits at high speed (see table 3-7) might be evaluated first.

3.2.6 Coordinated Multi Point

The pro's and con's of Coordinated Multi-Point (CoMP) have been discussed in TR 103 865. CoMP can be considered as interference mitigation technique to improve data throughput performance of the 5G NR FRMCS network. It can be distinguished between Downlink- and Uplink methods.

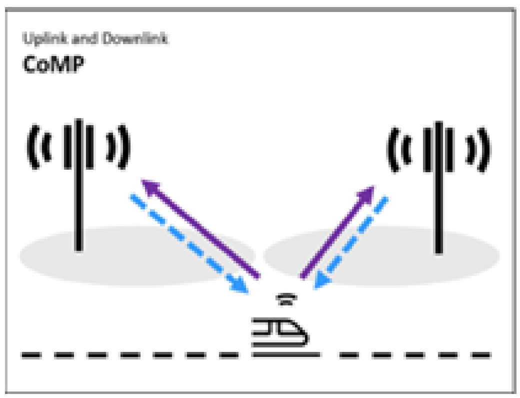


Figure 3-13: Coordinated Multi-Point

- In downlink this method mainly aims to reduce the interferences between cells. In rural areas with a low cell density and linear deployment, the gain seems to be very low. CoMP-like techniques can be implemented in 5G New Radio as part of the multi-TRPs (Multi-Transmission Reception Point) framework which includes Coherent and Non-Coherent Joint Transmission (CJT and NCJT), as well as Dynamic Point Selection (DPS). The cooperative set (CoMP set) is the set of TRPs that are participating in transmission to/from a given UE.
- In the Uplink CoMP can be used by combining received signals from a single train at several BS at the same time which will enhance reception quality. In the Erzgebirge Trial (based on LTE) gains of up to 20% of the medium throughput could be measured in cell border areas.
- Conclusion/recommendation for CoMP: as CoMP is a vendor-specific feature, it is considered as an optional configuration. It may be implemented on national basis as additional interference mitigation techniques to optimise the data throughput especially in urban area. Additionally, in FRMCS, UL CoMP is practically limited to two sites since any other additional site would normally be very far from the location of a single train. Therefore, it would receive a very low uplink power and no additional gain can be expected.

3.3 QoS aspects

FRMCS QoS requirements are defined in [FW-AT 7800, Chapter 14]. It is based on the different QoS requirements of the individual communication sessions with different priorities. Main KPIs are throughput, latency and packet reliability.

The signalling and enforcement procedures of the FRMCS QoS and priority framework are based on 3GPP mechanisms defined for the 5G System in transport stratum and the Mission Critical services (MCX) in service stratums.

The 3GPP QoS parameters include the 5G QoS Identifier (5QI), the Maximum Flow Bit Rate (MFBR), the Guaranteed Flow Bit Rates (GFBR) and the Allocation and Retention Priority (ARP). The FRMCS system shall support standardized 5QI values as shown in Table 3-8 [see 14.6.2.1 in FW-AT 7800].

Standardized 5QI
5
8
65
69

Table 3-8: Standardised 5QI for FRMCS

The FRMCS Quality of service framework for the transport stratum is described in [TS 103 TS 103 765-1 Transport Chapter 10: FRMCS Core Quality of Service Framework].

a) QoS is applied via PDU sessions (up to 15 per UE) and QoS flows (up to 63 per PDU session)
b) QoS is enforced at UE, gNB and UPF based on rules propagated from the UDM/PCF or pre-configured
c) QoS policy is controlled via Rx or N5 interface messaging from the FRMCS Service Server
d) The gNB can map multiple QoS flows with similar characteristics to a single Data Radio Bearer (DRB)
e) QoS flows can be of type GBR (Guaranteed Bit Rate), non-GBR and delay critical GBR
f) Each QoS flow is associated with a QoS profile, including
    i) A QFI (QoS Flow identifiers) based on 5QI
    ii) An ARP (Allocation & Retention Priority)
    iii) type specific & optional parameters
g) IP data is mapped (filtered) to QoS flows at UE (based on QoS rules) and UPF (based on PDRs) utilizing packet filter sets

First field trials to test the performance of FRMCS with different applications in a mobile environment has been conducted within the 5GRail Project [Ref 26].

As described in section 3.1.1 there is no straightforward relation between the coverage and the expected throughput values anymore. This also applies to other KPIs. Further studies and field trials are needed to map application QoS requirements to certain coverage planning parameters such as RSRP, SINR and coverage probability.

3.4 Sample calculation coverage and minimum available throughput

Radio planning plays an important role in the FRMCS network design. Accurate design is essential to ensure that the system will provide the required capacity and quality where it is needed. These radio network planning objectives are achieved through correct site location and cell settings and parameters, including antenna models, antenna heights, azimuth, and tilt angles, etc. Digital maps (Digital Terrain Model, clutter type and heights, …) and a calibrated propagation model are also required to have an accurate radio propagation calculation.

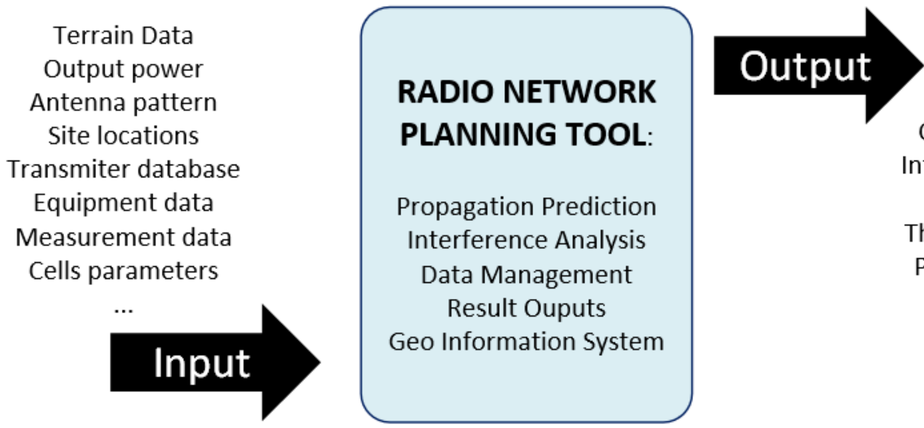


Figure 3-14: Radio network planning process

For an FRMCS radio planning based on 5G, the main cell parameters are:

- Frequency band (n100 and/or n101)
- Channel Bandwidth (5 MHz/10 MHz)
- Subcarrier Spacing: (15 kHz/30 kHz)
- Number of RB (e.g. 52 RB)
- Total output Power per gNodeB (e.g. 46 dBm (43 dBm per antenna element for MIMO 2x2))
- EPRE (Energy per Resource Element) power (e.g. 15 dBm)
- Output Power of the UE (e.g. 31 dBm for PC1)
- Number of Tx and Rx for gNodeB and UE (e.g. 4Tx/4Rx on the gNodeB side and 1Tx/2Rx on UE side)
- TDD pattern for n101 (e.g. 50% DL and 50 %UL)

Below are 2 examples of preliminary FRMCS radio planning based on GSM-R existing sites. The first is a radio planning in band n100 and the second is a radio planning in band n101. These simulations are performed in the north-east part of France.

Figure 3- 15: Digital elevation of the area

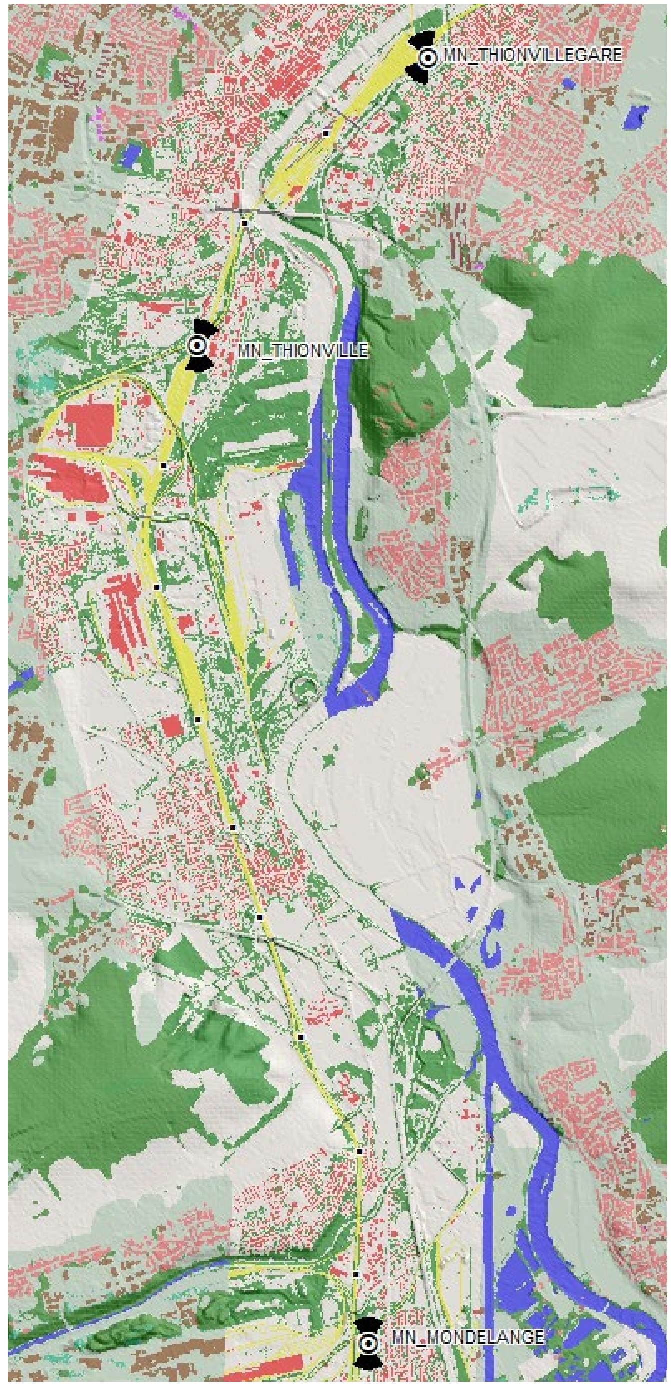


Figure 3-16: Land use of the area

The GSM-R site configurations are in the table below:

	Antenna Gain	Middle Antenna Height	Inter site distance
MN_THIONVILLE GARE	17 dBi	23.5m	
			3 km
MN_THIONVILLE	17 dBi	23.5m	
			8 km
MN_MONDELANGE	17 dBi	22.5m	

Table 3-9: GSM-R site configurations

3.4.1 Radio planning in band n100

For the first stage, the radio planning is based on a carrier of 5 MHz. The technical parameters used for the simulator are listed in the table below:

	gNodeB	UE
Frequency band	n100	
Bandwidth	5 MHz	
Subcarrier Spacing	15 kHz	
TDD pattern	----	
Number of RB	25	25
Total output Power	46 dBm	31 dBm
EPRE Power	18 dBm	
Antenna gain	17 dBi	0 dBi
Antenna height	GSM-R antenna height	4m
Antenna Azimuth	GSM-R antenna azimuth	---
Cable Loss	Based on GSM-R cable losses	6 dB (aligned with chapter 4)
Number of Tx	2	1
Number of Rx	2	2
MIMO technology	Tx and Rx diversity	Rx diversity
Cell load	25%	
Maximum Modulation Scheme	256 QAM Depending on SINR value	64 QAM Depending on SINR value

Table 3-10: n100 planning configuration

To compare the coverage of GSM-R and FRMCS networks, the difference of channel bandwidths and EIRP between the 2 systems must be taken into account:

• The GSM-R coverage was calculated with a typical EIRP of 58 dBm for a channel bandwidth of 200 kHz.

• The FRMCS coverage was calculated for the RSRP by the software tool with a typical EIRP of 32 dBm for a single subcarrier of 15 kHz (with the spacing between the subcarriers based on the numerology).

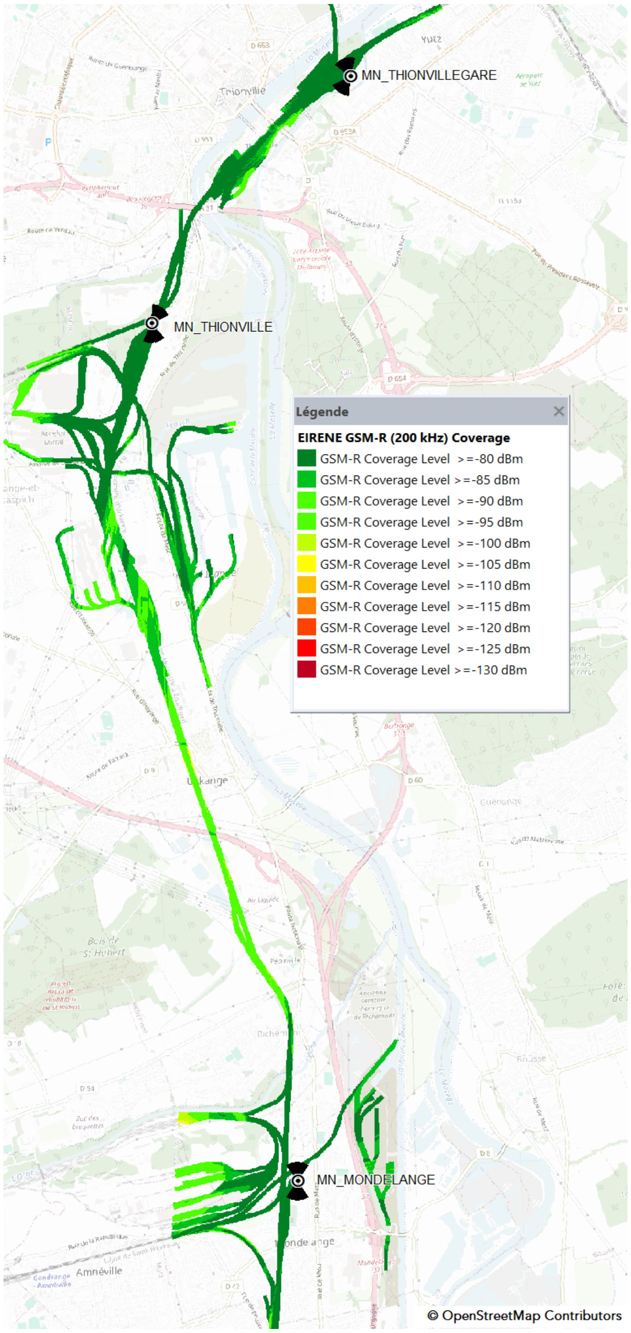


Figure 3-17: GSM-R EIRENE Coverage

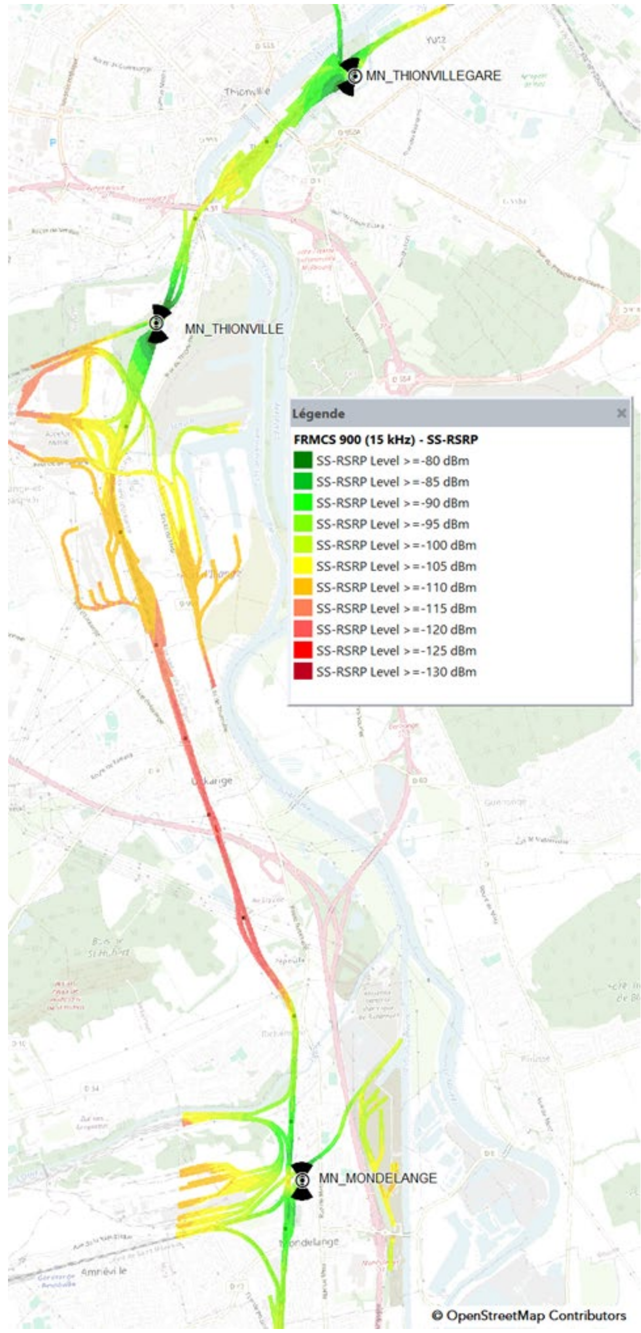


Figure 3-18: SS-RSRP - FRMCS 900

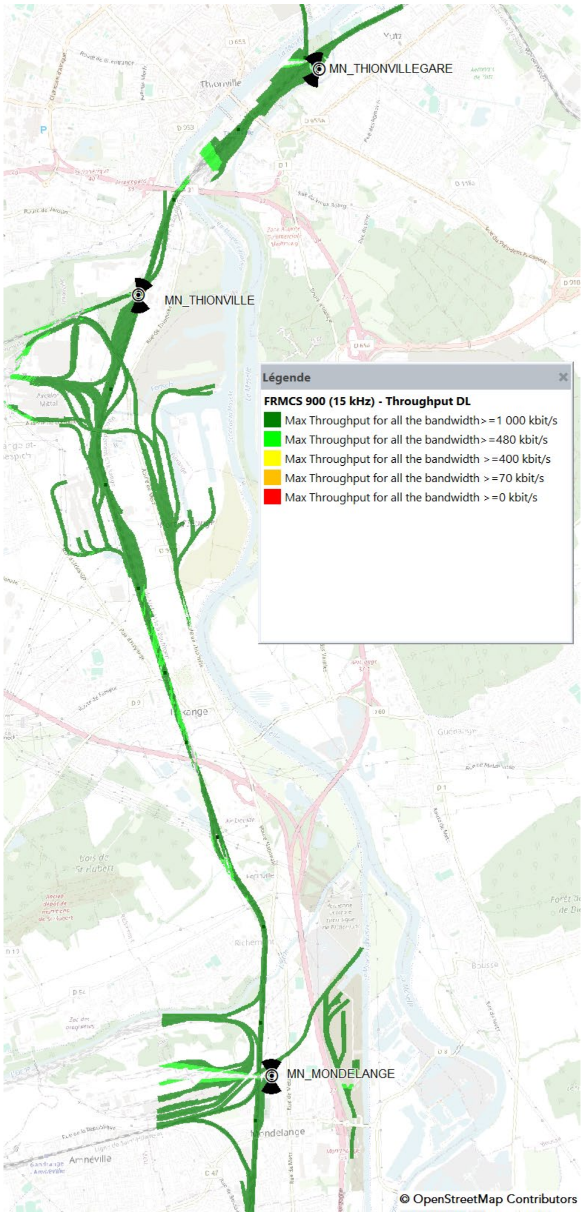


Figure 3-19: FRMCS 900 Downlink Throughput

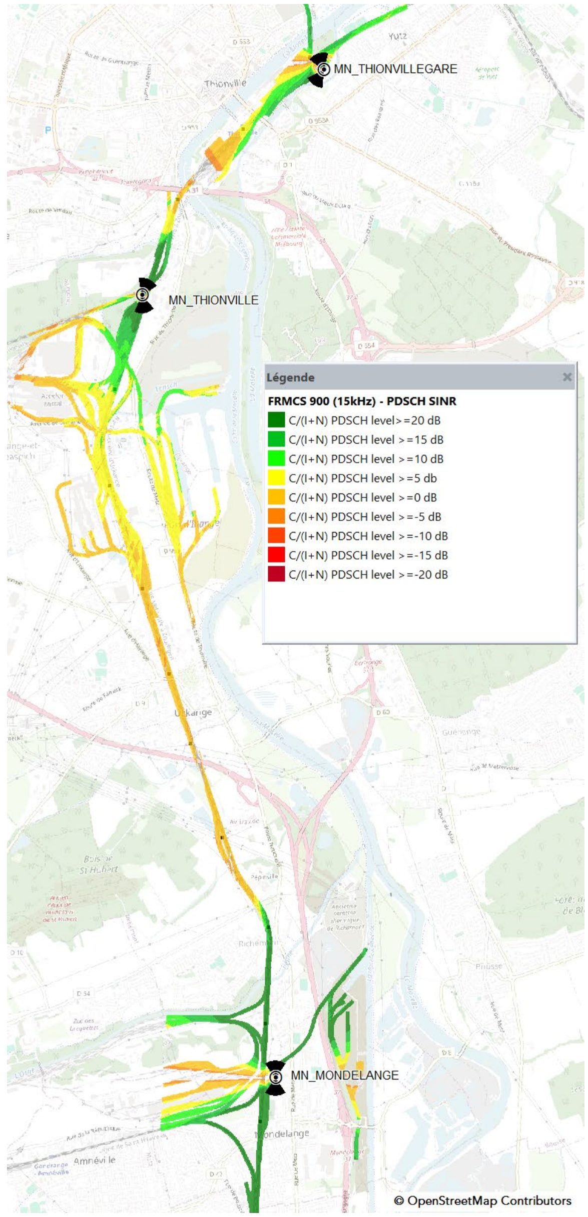
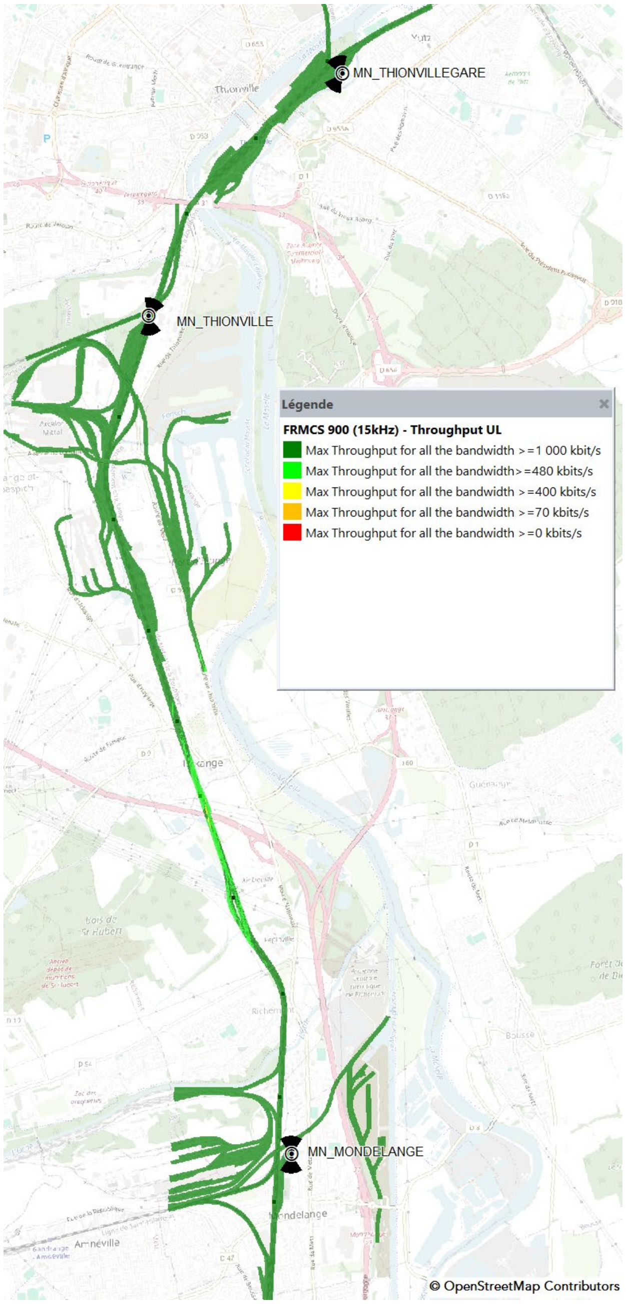


Figure 3-20: FRMCS 900 Downlink C/(I+N)



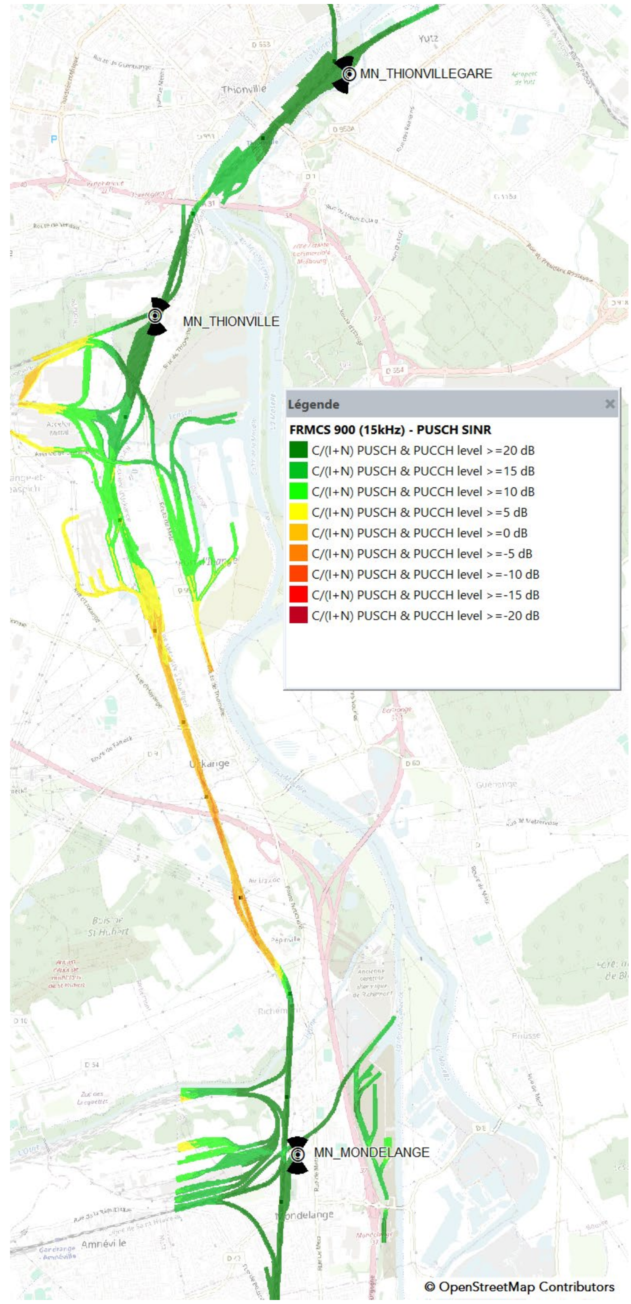


Figure 3-21: FRMCS 900 Uplink Throughput

Figure 3-22: FRMCS 900 Uplink C/(I+N)

3.4.2 Radio planning in band n101

Technical parameters for band n101:

	gNodeB	UE
Frequency band	n101	
Bandwidth	10 MHz	
Subcarrier Spacing	30 kHz	
TDD pattern	50 % DL – 50% UL	
Number of RB	24	24
Total output Power	46 dBm	31 dBm
EPRE Power	21 dBm	
Antenna gain	17 dBi	0 dBi
Antenna height	GSM-R height	4m
Antenna Azimuth	GSM-R antenna azimuth	---
Cable Loss	Extrapolation from GSM-R cable losses	6 dB (aligned with chapter 7)
Number of Tx	2	1
Number of Rx	2	2
Cell load	25%	
MIMO technology	Tx and Rx diversity	Rx diversity
Maximum Modulation Scheme	256 QAM Depending on SINR value	64QAM Depending on SINR value

Table 3-11: n101 planning configuration

To compare the coverage of GSM-R and FRMCS networks, the difference of channel bandwidths between the 2 systems must be taken into account:

• The GSM-R coverage was calculated with a typical EIRP of 58 dBm for a channel bandwidth of 200 kHz.

• The FRMCS coverage was calculated for the RSRP by the software tool with a typical EIRP of 35 dBm for a single subcarrier of 30 kHz (with the spacing between the subcarriers based on the numerology).

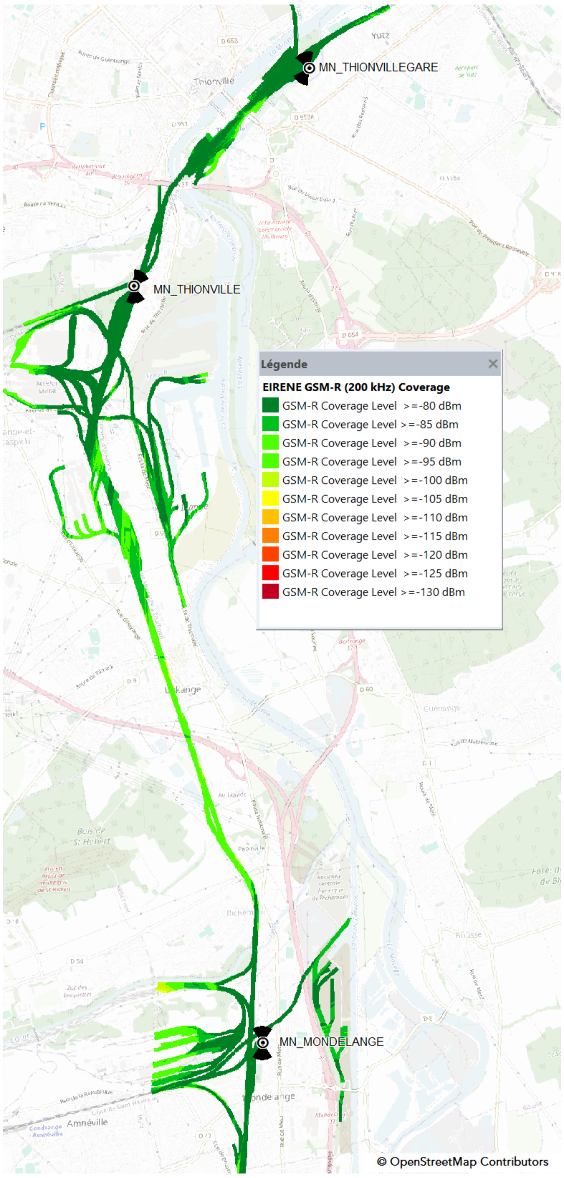


Figure 3-23: GSM-R EIRENE Coverage

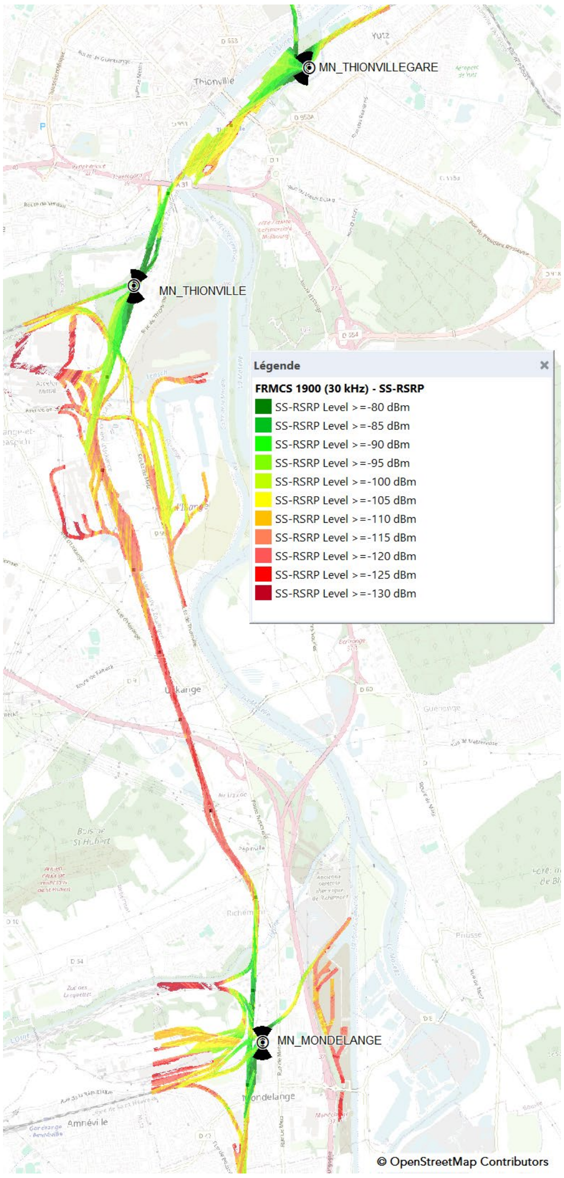


Figure 3-24: SS-RSRP - FRMCS 1900

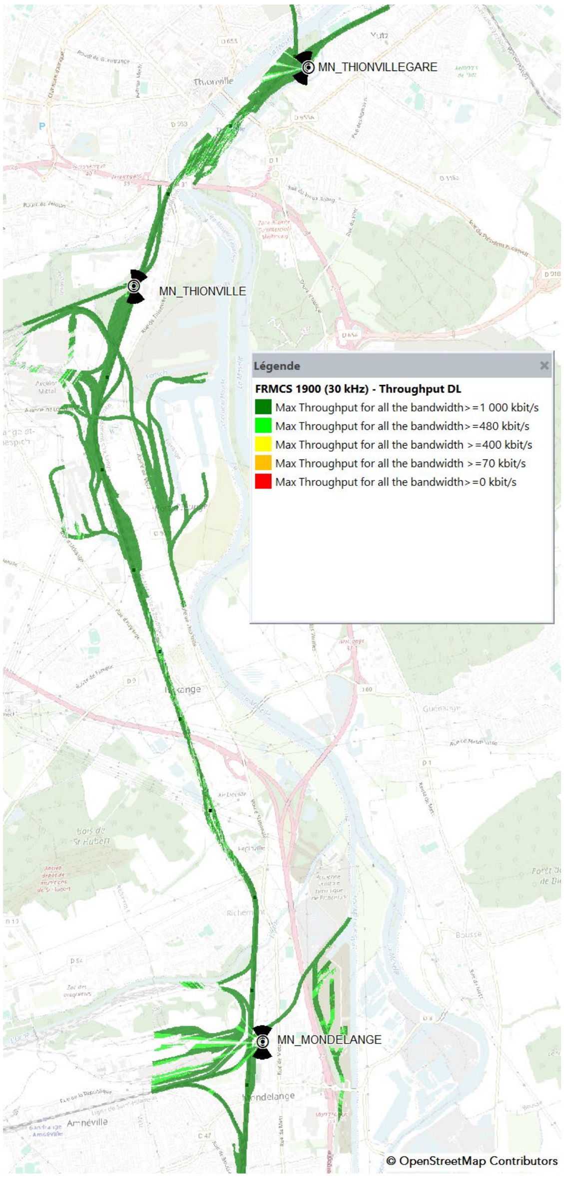


Figure 3-25: FRMCS 1900 DL Throughput

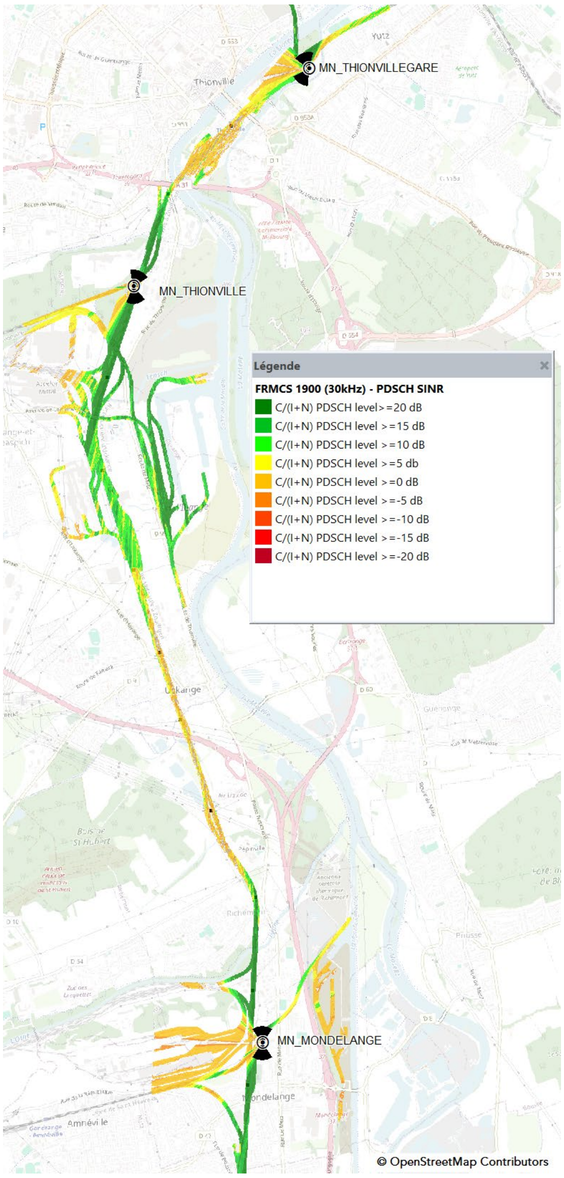


Figure 3-26: FRMCS 1900 Downlink C/(I+N)

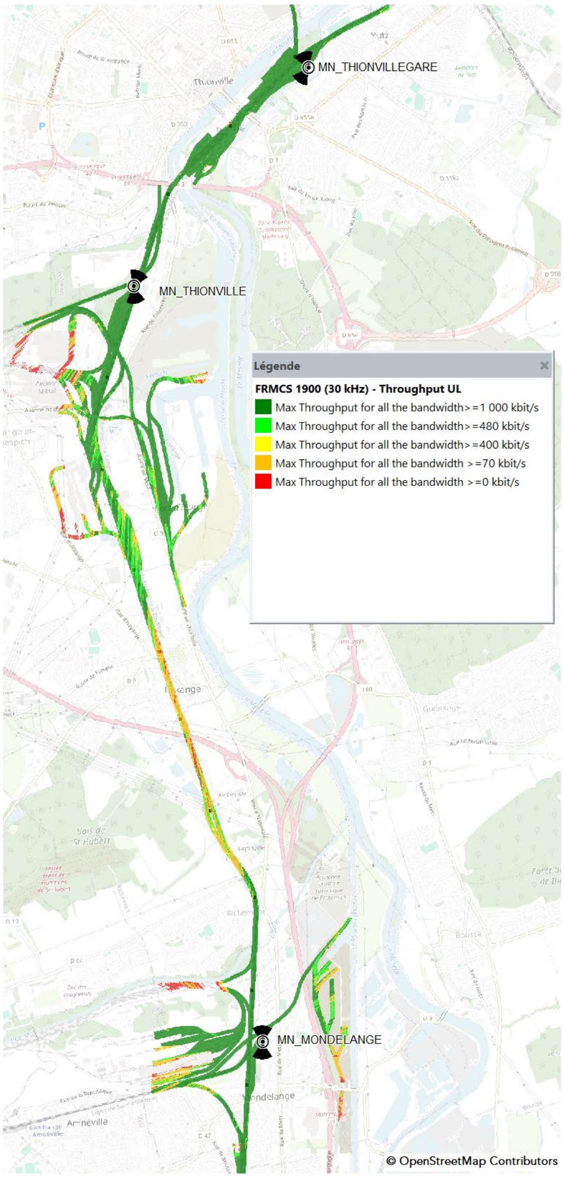


Figure 3-27: FRMCS 1900 Uplink Throughput

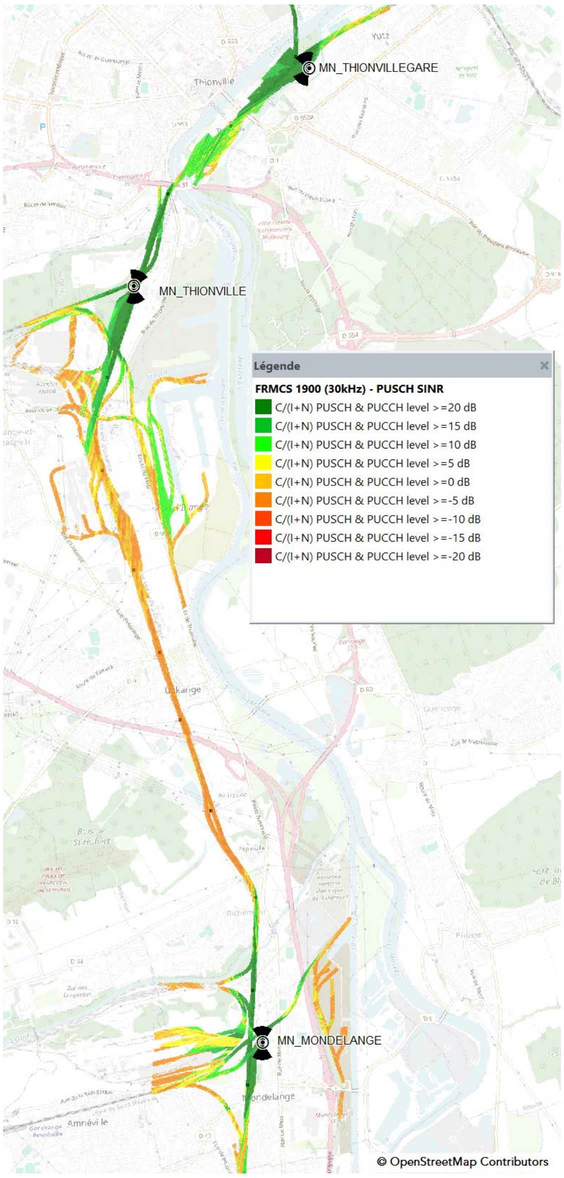


Figure 3-28: FRMCS 1900 Uplink C/(I+N)

The C/(I+N) coverage above correspond to the raw C/(I+N) and does not consider digital enhancements such processing gain of MIMO scheme.

Throughput maps are derived from the SINR calculation considering the modulation schema and a mapping table, converting SINR into MCS. Other KPI such as RSRQ, RSSI, Noise Level, Bit Error Rate, are also available in most radio planning tools.

The need of site densification depends on the minimum SS-RSRP FRMCS level coverage in the area and the minimum data throughput according to the services that need to be supported.

5G networks are sensitive to interference levels, so particular attention needs to be paid to optimising radio planning.

Note: In this example, the propagation model is not calibrated. Further optimisations are also needed to enhance the results. Further analyses are required to better understand the radio planning calculation.

3.5 Redundancy in radio coverage

3.5.1 Different possibilities

This section addresses the different possibilities to create redundancy in the FRMCS radio coverage.

First, it should be recalled that the solution of double coverage used in some GSM-R networks to increase the availability of the system according to the requirement of some specific application (e.g. ETCS Level 2) is not a target itself. This technical solution has been designed and implemented according to the specific 2G network architecture and the availability of the different equipment constituting the GSM-R network (BTS, BSC….). This choice has also been conducted by the time needed to re-establish a GSM-R call (based on circuit switch data) after a drop call.

The different possibilities (non-exhaustive) to implement redundancy in a 5G NR system could be based on:

- Redundancy of some RAN equipment (CU/DU and/or RU by cross-connection antennas);
- Distance between Radio sites (in order to have overlap between adjacent cells);
- Dual layer on co-located site using both frequency band (n100 and n101);
- Dual layer on co-located site using two adjacent 5 MHz carriers in band n101;
- Dual Connectivity (expected as 3GPP R19 UE feature).

In summary, the choice for resiliency in the RAN architecture has to consider:

- the resiliency of each equipment constituting the 5G FRMCS network (this information depends on the equipment manufacturer);
- the minimum distance between 2 adjacent radio sites;
- the time to establish (or re-establish) a call in a 5G NR system (this is FFS);
- the evolution of the spectrum regulation and industry products.

3.5.2 Cross-connect

Cross-connect the RUs on a specific radio site to different antennas. In such a configuration, half of the antenna ports on an RU are connected to the first antenna and the other half to the second antenna. The same principle applies then to the second RU. The idea behind the use of this cabling configuration is that a cell becomes, logically speaking, divided across two different RU halves. A specific configuration at the DU/CU side needs to be done to handle this division of the signal between the two RUs. By proceeding as such, in case one of the RUs fails, a total loss of coverage on a sector will not occur but will only result in a degradation of maximum throughput of the two cells.

3.5.3 Reducing inter-site distance

By reducing the distance between radio sites, a sufficient overlap is achieved between second tier neighbour radio sites. In the event of a radio site failure, the second tier radio sites are then still in condition to provide coverage and quality in degraded mode with a minimum acceptable throughput for the required services on the rail section. A particular attention to the interference levels and mitigation techniques is required for this case as the interference level generated in the normal functioning (non-degraded) mode may substantially be increased.

3.5.4 Co-located dual layer

A co-located dual layer of the n100 and n101 bands is configured at each radio site. In this configuration, a layer of one band is always present to take over the traffic in case the layer of the other band fails. To limit the mast occupation and load, the RUs can be dual band but then, in the event an RU fails, this could potentially generate a coverage loss on both bands. A combination of cross-connect, as explained before, together with dual band RUs will increase the resiliency of the solution and only generate a throughput degradation when a failure occurs. In the design of this configuration, both n100 and n101 coverage and quality levels need to be sufficient to support the required services by themselves.

3.5.5 5MHz dual layer in n101

By creating two 5 MHz carriers in the 10 MHz of the n101 band, an IM can benefit of the advantages of a dual carrier configuration. This configuration acts in a similar way as the dual band layer system explained before but within the same band, so the considerations and remarks (dual carrier RUs or two single carrier RUs, cross-connect) are still applicable. Note that currently industry only supports 30kHz SCS in FR1 TDD which would make such usage unavailable.

3.5.6 Dual Connectivity

By implementing the expected Release 19 5G Dual Connectivity feature in the split Signalling Radio Bearer mode, the network signalling can be carried via both the Master Node and the Secondary Node. This allows the network to interchange the MN and SN roles and hence continue the existing data session. The current status of this feature is inconclusive (see Table 4-1).

3.5.7 Redundant uplink rural coverage

As an example for redundant uplink rural coverage, the following case study from the Finnish Transport Infrastructure Agency (FTIA) may be used. The Finnish Transport Infrastructure Agency in 2021 ordered a radio network planning study for typical base station distances in rural and in urban areas (see FTIA report on FRMCS 900 MHz Nominal Plan – May 11th, 2021, presented in UGFA Ad-hoc meeting June 15th 2021). In these simulations base stations were placed on existing masts or at the top of existing building. The rural area simulation was done for 900 MHz FRMCS with the following details:

- UE Tx power +31 dBm
- Train radio antenna height 4 m, antenna gain was 0 dBi, cable loss 3 dB
- downlink direction noise figure was 5 dB
- external interference margin in 900 MHz uplink was 6 dB. This 6 dB noise was combined with 5 dB noise figure to have a compound noise figure value of 8.5 dB for planning tool.
- For BS side cable loss was 0.5 dB, antenna gain 15 dBi, X-pol antenna with 60° beam width and 60 W Tx power.
- Noise figure in uplink was 3 dB
- external interference margin for 900 MHz uplink was 3 dB. This was combined with 6 dB noise figure for planning tool.
- MIMO was not used.
- X-pol BS antenna characteristics, like polarisation loss were included for tuned propagation model.
- diversity reception at the BS

Additional requirement of minimum data throughput for both uplink and downlink were 100 kbps. There was also redundant coverage requirement meaning that every second base station may be out of service and 100 kbps requirement shall still be fulfilled.

Planning for rural area was made for 190 km long rail track. Total number of BS was 13 and with 12 BS gaps gives 15.8 km inter-site distance. BS antenna heights were between 20 m and 80 m. Typically mast is built in rural area at the top of local hill, and this increases effective antenna height compared to that at ground level, where railway lines are typically located.

In practice the uplink direction was the limiting factor for site distances. Data are presented for throughput values in uplink for Figures 3-29 and 3-30 and in downlink for Figure 3-31. Figures 3-29 and 3-31 are when every base station was in service and Figure 3-30 is when every second base station is out of service. The legend of all figures shows the distribution of different data throughput in kbps using different colours. Interesting view is the effect of redundancy requirement on data throughputs. If single layer requirement is 100 kbps, then more than 73 % of the rail track will fulfil 5 Mbps requirement in uplink (see Figure 3-29, data speeds in kbps)

This analysed track is a single line and there cannot be another train in close proximity due to safety rules. This leads to the situation that there were no noticeable interferences from other cells and in the simulation there was a maximum of one UE per cell.

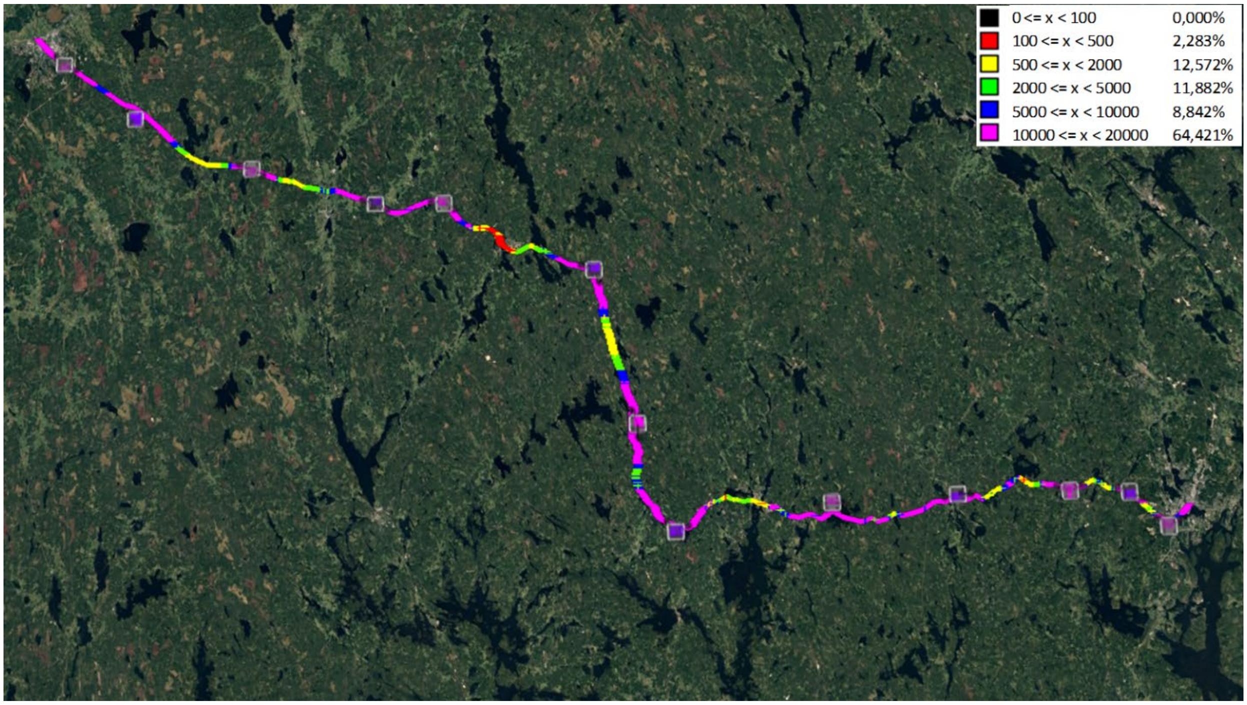


Figure 3-29: FRMCS 900 Uplink Throughput all cells

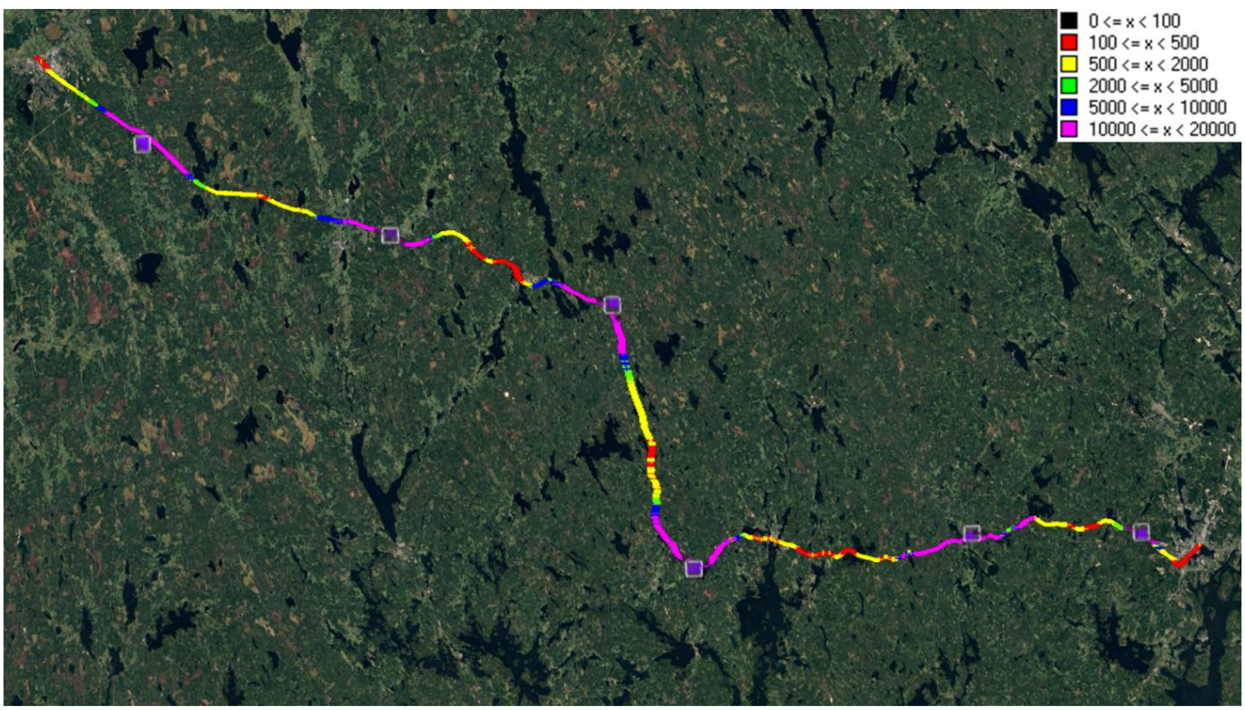


Figure 3-30: FRMCS 900 Uplink Throughput every other cell

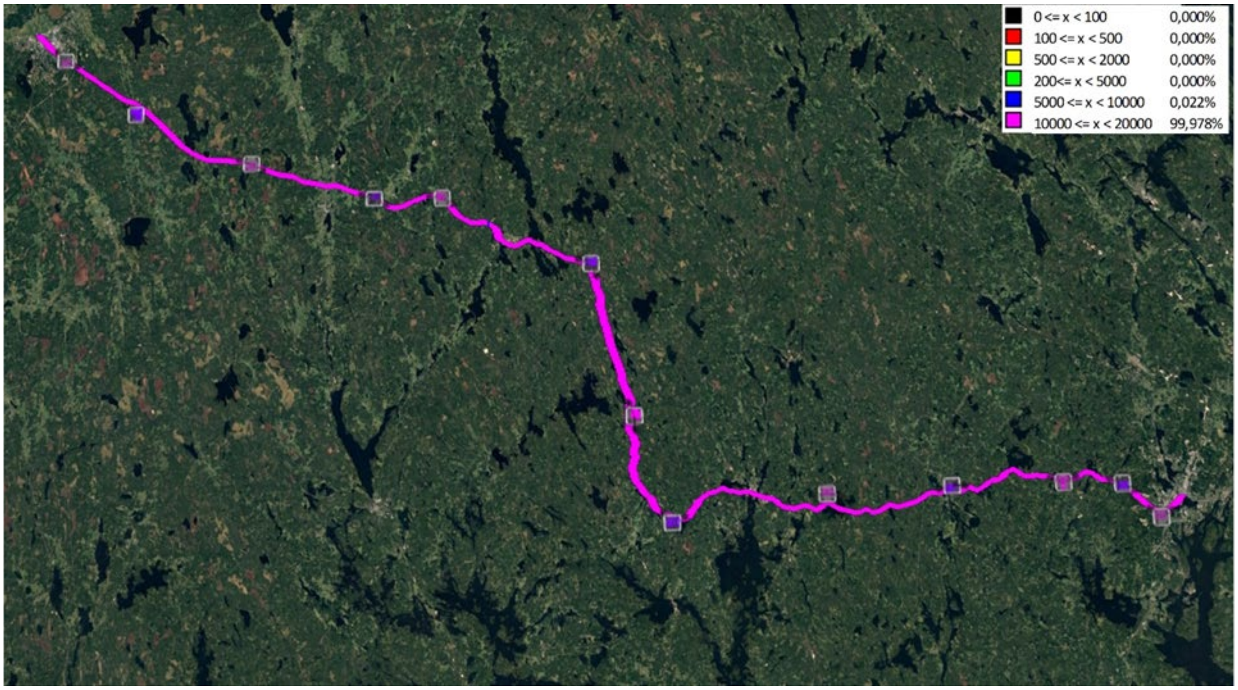


Figure 3-31: FRMCS 900 downlink data throughput with every BS in service

4 FRMCS On-board aspects

4.1 Characteristics on-board radio

Specific requirements on the radio performance of the FRMCS on-board equipment have been specified in the ETSI TS 103 793 FRMCS Radio Characteristics. One purpose of this specification is to ensure compliance of FRMCS equipment with the ECC DEC(20)02.

4.1.1 High power UE

It is expected that all FRMCS on-board radio's (UEs) will be based on Power Class 1 (31 dBm conducted output power).

As the UE will indicate to the FRMCS base station that it has the PC1 capability, the BS will adjust its transmit power and MCS to reflect this, hence matching the downlink coverage range with the enhanced uplink coverage range[13].

4.1.2 3GPP UE features

The following 3GPP features are recommended to be supported by the on-board UEs in order to ensure interoperability and to optimise the FRMCS RAN performance:

Release	**Feature**	**Reason**	Preliminary recommendation for interoperability	Preliminary recommendation for performance
17	Support RMR band n100	900 MHz	√	
17	Support RMR band n101	1900 MHz	√	
17	HST FR1*	High speed train		√
18	PC1	31 dBm	√	
18	Less than 5 MHz channel bandwidth	Migration using n100	√	
18	CHO	Improved Hand-over		√
Requested for 19**	CA/DC	Carrier aggregation and Dual Connectivity		√
Requested for 19**	2x2 MIMO (UL)	MIMO		√

Table 4-1: Overview UE features

13 According to the 3GPP specifications PC3 is the default power class for every 3GPP band

* No extensive QoS was studied as the Work Item was targeting Best Effort.

** The current status is inconclusive.

4.2 On-board antennas and cabling

As the gain of on-board antennas and allowed cable attenuation directly affecting the FRMCS link budget, the design of the FRMCS air interface needs to reflect this. A required network coverage levels for FRMCS need to be carefully defined to find a suitable compromise between physical on-board integration requirements and link budget for interoperability purpose.

4.2.1 Train integration issues

The possibilities to integrate on-board equipment and antennas in a train are often restricted. For on-board equipment integration space, electrical power, and possibly ventilation is needed. Antennas are often competing with pantographs, other superstructures, and other antennas on the roof of trains.

Figure 4-1 shows an example of installed on-board GSM-R systems (cab radio and ETCS). The distance between the location of on-board equipment (i.e. TOBA for FRMCS) and antennas affects the necessary cable length and hence attenuation. Often different cable types are combined to allow low cable attenuation for long distances and flexible cables for last meters integration through walls etc.

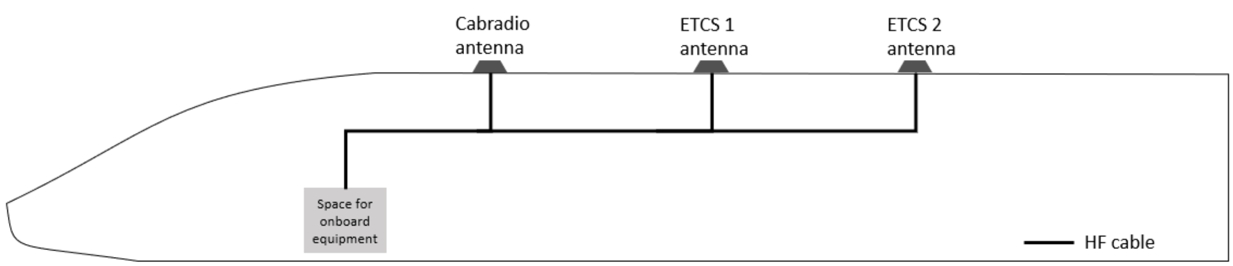


Figure 4-1: GSM-R cab radio and ETCS setup

The following table gives an example of cable lengths and related cable losses for 900 MHz taken from recent installation in a high-speed train. As FRMCS will be using higher frequencies (1900 MHz n101 band and potentially several MNO frequencies up to 3800 MHz), the effects of the increasing attenuation of coaxial cable for higher frequencies needs to be taken into account. The estimated cable losses for n101 (1900 MHz) and n78 (3400-3800 MHz as the highest envisaged MNO frequency) are also shown in Table 4-2.

	Cabradio installation	**ETCS 1 installation**	**ETCS 2 installation**
Total cable length [m]	6.50	12.00	18.00
Cable loss [dB] Low band: 900 MHz	1.30	1.90	2.50
Cable loss [dB] Mid band 1900 MHz	1.60	2.50	3.40
Cable loss [dB] High band 3600 MHz	2.40	3.60	4.90

Table 4-2: cable losses for different frequencies

The table shows that especially for the mid and high frequency band the losses of the long cables are significantly high. Additional losses for connectors (approximately 0.1dB/connector) may need to be added.

4.2.1.1 Cable losses for FRMCS integrated or distributed TOBA setup

For better understanding of the concept of integrated and distributed TOBA box, the on-board FRMCS architecture model must be considered. Referring to the on-board FRMCS architecture model, Telecommunication On-Board FRMCS (TOBA) includes the so-called Gateway Function and the Radio Function with radio module(s). Radio module(s) may also be called modem(s). The interface between Gateway Function and Radio Function is called OB_{RAD}. In addition to the integrated approach of both functions in a single TOBA box, OB_{RAD} can enable a distributed approach for the realisation of Gateway Function and Radio Function. When the Radio Function is located closer to the on-board antennas, cable losses can be minimised and higher EIRP levels may be achieved.

Within EIRENE for GSM-R installations, maximum 6 dB losses between antenna and receiver inputs (including a margin of 3 dB for ageing and other effects) are defined. Discussions with manufacturers, RUs and measurements indicate that aging normally does not result in higher cable losses. Due to the constant vibrations on a running train, in the main problem is in connectors which are difficult to map to a certain value of additional loss.

Table 4-2 shows the dependency of cable losses and frequencies. Losses are increasing with increasing in frequency. However, allowing higher losses for higher frequencies (n101) will directly affect network planning and the number of necessary base stations, which already is increased due to the less favourable propagation conditions at the higher frequency.

For FRMCS in n100 and n101 assuming maximum loss of 6 dB seems to be a good compromise. It would allow e.g. worst case installations with up to approximately 20 m cable length at n101 which might become necessary in some trains:

- Total loss = 5.6 dB
    - Cable loss (1900 MHz): maximum 4 dB
    - Connector losses (6 x 0.1 dB) = 0.6 dB
    - Filter loss: 1 dB
- Due to the very small margin those installations might need more maintenance, but it would still meet the maximum loss of 6 dB.

4.2.1.2 Distributed TOBA setup with remote radio function

Depending on the size of the on-board FRMCS equipment, an installation closer to the antennas might not be possible in some train types.

The usage of a remote radio function can solve the problem of limited space in some types of train with installation of radio modem closer to the antennas as the size of only the radio functions should be smaller than the complete TOBA equipment. This could help to significantly reduce cable losses. The following table shows cable losses of 3 different coaxial cables with a rather small diameter (5.5-7.8 mm) that are often used for installations that need some flexibility as the 'last meter' towards the roof.

	Huber & Suhner SPUMA 240	RFS SCF14-50JFN	Huber & Suhner SX_04172_B-60
Total cable length [m]	2	2	2
Cable loss [dB] Low band: 900 MHz	0.5	0.4	0.54
Cable loss [dB] Mid band 1900 MHz	0.72	0.54	0.82
Cable loss [dB] High band 3600 MHz	1.2	0.8	1.2

Table 4-3: Cable losses versus frequency

The use of a remote radio function would further reduce the cable losses. A total loss of cables and connectors of maximum 2 dB is expected here. However, it might make maintenance of the equipment more costly as accessibility of installations e.g. under the train-roof can be more time-consuming compared to an installation in a cabinet.

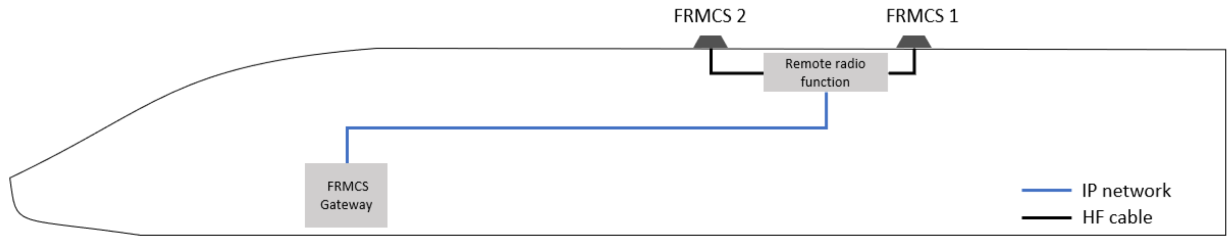


Figure 4-2: FRMCS setup with remote radio function

4.2.1.3 Integrated remote radio module + antenna

Another possibility could be the installation of the remote radio function / modem within the antenna housing. First products with 5G modems and an integrated embedded compute unit (CPU) are already on the market. This allows very low cable losses between modem and antenna. Maintenance will possibly need roof access and hence may be more costly and time intensive. Thermal issues and the integration of potentially needed filters are issues that need to be studied further[14]. For a very short internal HF-cable plus connectors losses of ca. 1 dB seems to be reasonable.

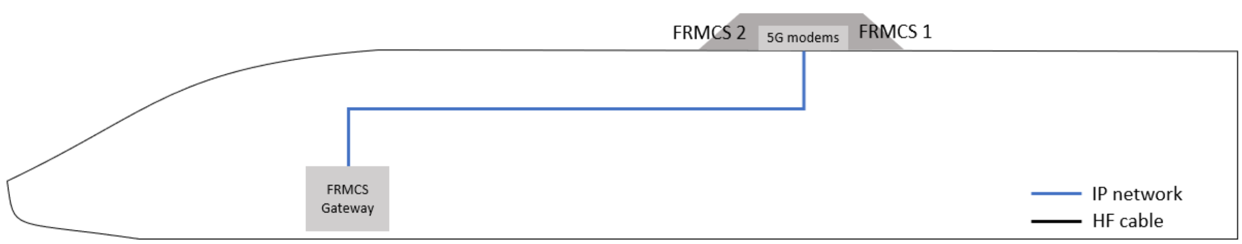


Figure 4-3: FRMCS setup with radio function integrated in antenna

The use of this type of architecture allows the placement of the antennas in a flexible way, because losses of the radio frequency cables are eliminated. This means the integrated remote radio module plus antenna can be positioned in the best spot for on-board installation and also further away from interference sources like e.g. GSM-R and MNO antennas. However, the size of the integrated unit and the layout of other systems on the train rooftop (and related safety requirements) may limit the on-board implementation.

[14] According to information from one industry company, thermal design based on today's available antenna construction can handle and has been tested up to 100 degrees Celsius. This would also allow it to handle dissipation power as well of a high-power radio.

4.2.2 On-board coexistence

To archive high availability for the 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 need to be avoided. Baseline for the evaluation work UGFA are the relevant ECC Reports 313 and 314. Additional, UNITEL presented in 2021 a study on On-Board antenna deployment [ref 15].

The most relevant disturbance mechanisms are blocking and out-of-band emissions. Spurious emissions and intermodulation are additional interference mechanisms. A proper isolation/decoupling needs to be ensured between GSM-R and FRMCS in the RMR bands as well as between GSM-R, FRMCS and the used MNO bands.

UNITEL study of 2021 on On-Board antenna deployment [Ref 15] shows a worst-case analysis of on-board coexistence. Due to non-availability of band n100/n101 parameters, data related to band n8 and band n39 has been used in that study.

The analysis is based on several worst-case assumptions:

- Worst case spurious emissions behavior of the interfering system;
- Worst case combination of UE (train) at the coverage edge (highest sensitivity needed), Tx transmitting with highest power;
- Noise limited system, no network-self interference.

Figure 4-4 shows the worst-case scenario analysed in the UNITEL study, where the 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.

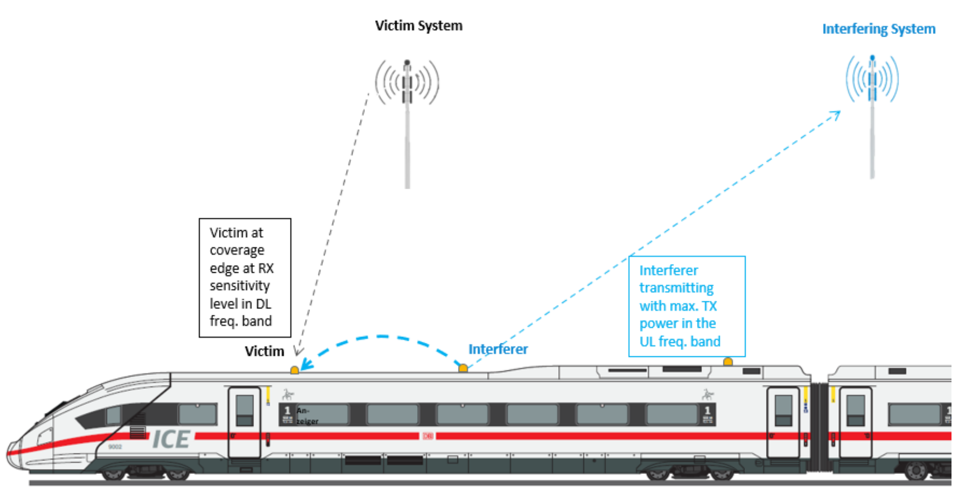


Figure 4-4: Worst case scenario of on-board interference

Since FRMCS standardization is advanced within 3GPP and ETSI, as well by UIC specifications, a further assessment of the input parameters and recalculation of the isolation requirements has been proposed to UNITEL by UGFA [Ref 22].

The study should take band n100 & n101 into account and also consider recommendations given in ECC Report 249 [Ref 24].

Other topics that might influence the coexistence study are the nature of interference and uplink limited 5G networks.

4.2.2.1 Additional RF filtering

Depending on frequency relationships of multiple frequency bands running in parallel and configuration of the radio-modules, the effects of interfering signals may be reduced by the use of one or more RF filters in the receive or transmit paths. The radio modules may be used in several different combinations, e.g. specific radio module(s) for RMR n100 + n101 bands only, for RMR n100 + n101 + one or more MNO frequency bands, for only MNO bands, etc.

The initial evaluations from UNITEL [see Ref 15] shows that especially the adjacent MNO frequency bands (n8 and n1) lead to very high isolation requirements. This requirement combines with being adjacent to the used frequency band would increase the necessity to install additional filters.

Depending on the necessary filter capabilities different filter types that come in different size and weight might become necessary. The selection of MNO frequency bands running in parallel to the critical RMR bands should be a compromise between available coverage of those bands and the implementation possibilities, costs and size/weight of the filters.

As any such a filter solution will create some kind of additional insertion losses. Note that in this document these filter losses are assumed to be part of the total maximum 6dB cable losses between a radio module and the antenna.

4.2.2.2 Train roof space

The necessary isolation between different systems can be provided by applying additional filters and/or separating the antennas in space.

Train roof space comes various sizes and superstructures which may make the installation of multiple antennas challenging. Especially within the migration phase, also isolation/decoupling of GSM-R and FRMCS antennas needs to be considered, in view of the mutual coupling effects.

Figure 4-5 shows the worst-case on-board deployment scenario, very small roof setup as presented to UGFA in an industry session. It assumes two FRMCS radios with antennas connected, a cab radio and two EDOR antennas (ETCS 1 and ETCS 2) on a 2.5mx 2.5m roof.

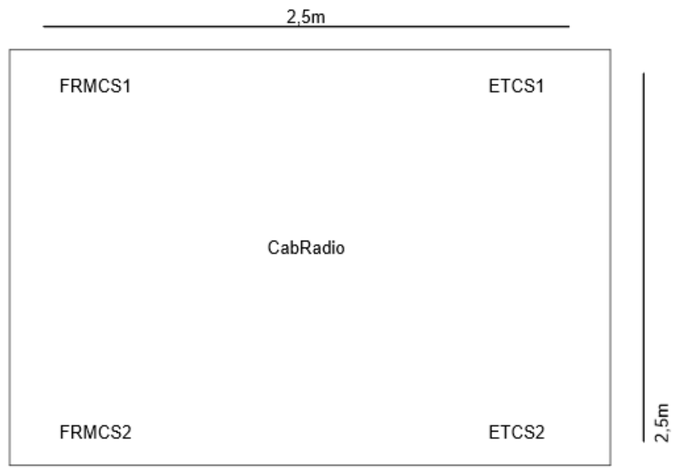


Figure 4-5: GSM-R and ETCS plus FRMCS antennas

If the relevant system parameters would be verified in a way that integration is possible here, other installations with more space on the roof would also be realisable.

4.2.3 Number of antennas (MIMO, etc.)

To be in line with 3GPP specification 3GPP TS 38.101, the required minimal setup for FRMCS is 2 antennas (1 for Tx/Rx, 1 for Rx only).

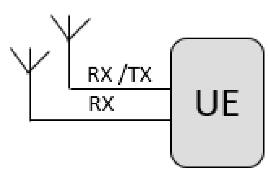


Figure 4-6: UE antenna configuration

The antenna elements might come in a single housing (SISO antenna), or MIMO antennas with multiple elements in one housing might be used. Care needs to be taken connecting the Tx-outputs of two different FRMCS modems (i.e. with PC1) to one MIMO antenna as isolation between the elements is limited (~15-20 dB for vertically polarized antennas, also depending on the frequency band, more for cross-polarised antenna elements).

For FRMCS additional and new types of antennas in most cases will need to be installed on trains and locomotives. These are likely to require additional efforts for design, verification and implementation onto train/locomotive roofs.

4.2.4 Train antenna gain

For determining the radio link budget, the effective gain of the train antenna is an essential element. As the train roof often is not a perfect flat antenna mounting surface with additional obstacles, the surrounding of the antennas may affect the antenna pattern and the antenna gain.

When using MIMO, antennas containing multiple antenna elements in one housing might become feasible, this may limit the need for additional antenna mounting locations.

With multiple antenna elements in one housing (e.g. MIMO antennas) the gain of one antenna directed towards the other is always slightly lower due to the isolation needed between the elements. The following antenna patterns show an example of a 2x2 MIMO antenna. (H&S 1399.99.0130 (2X2 MIMO) with ground plane). Note that to obtain the antenna gain at a specific azimuth and elevation, the gain for the frequency as given in the brackets below must be added to the value in the antenna pattern.

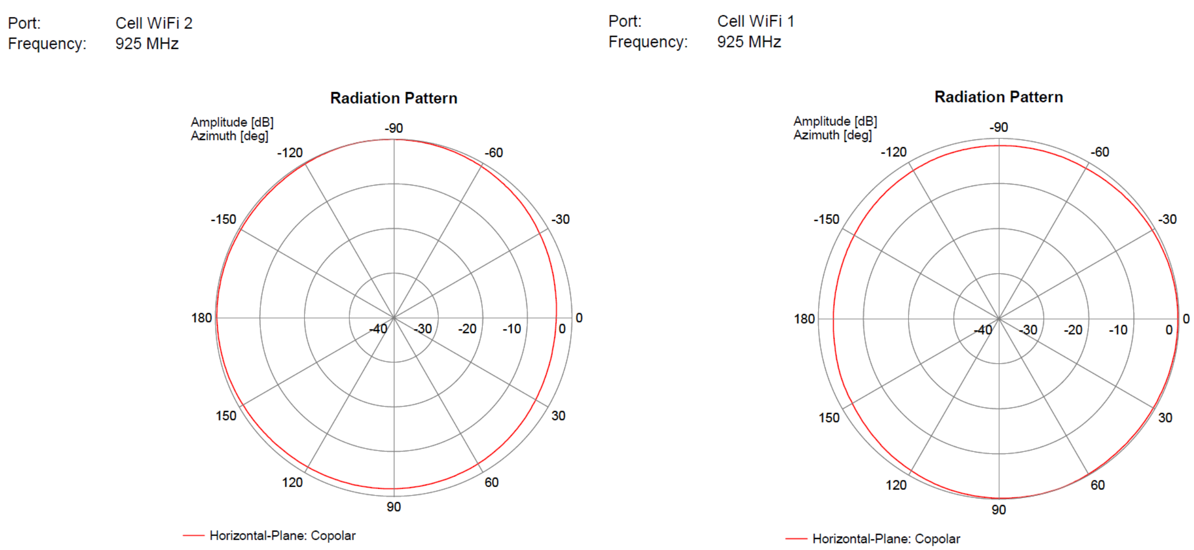


Figure 4-7: Horizontal pattern@ 925 MHz (H&S 1399.99.0130; gain ~7 dBi)

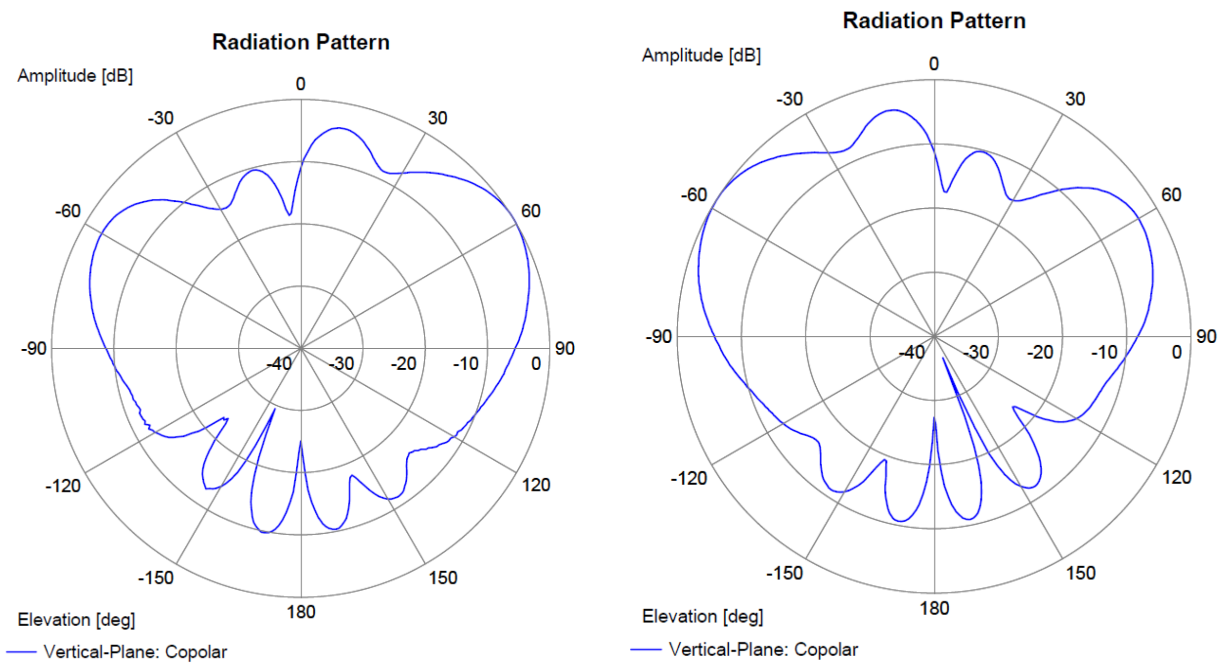


Figure 4-8: Vertical pattern@925 MHz (H&S 1399.99.0130)

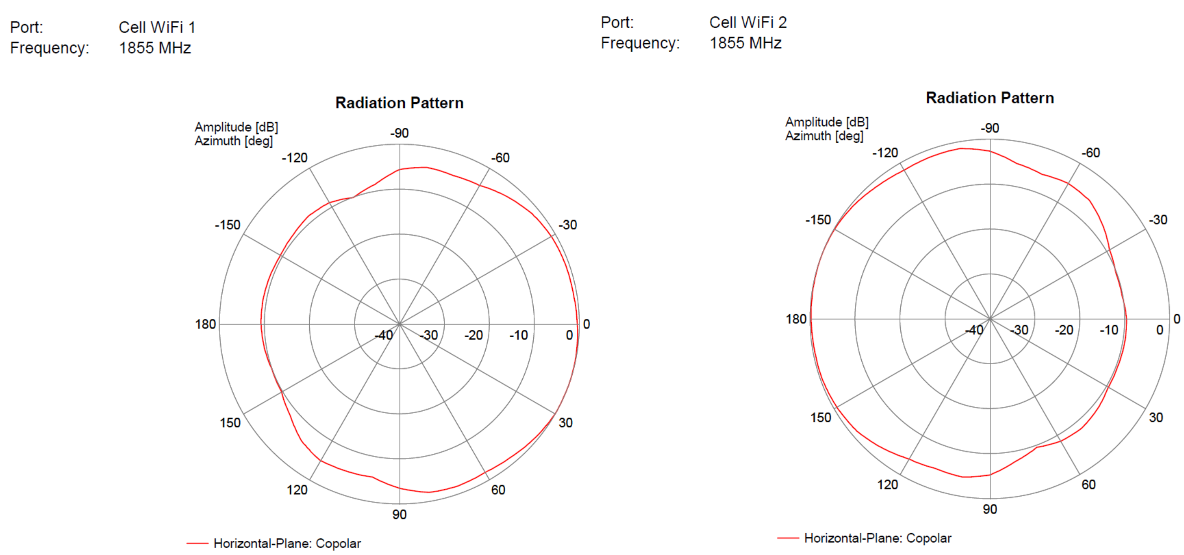


Figure 4-9: Horizontal pattern@1855 MHz (H&S 1399.99.0130; gain ~9 dBi)

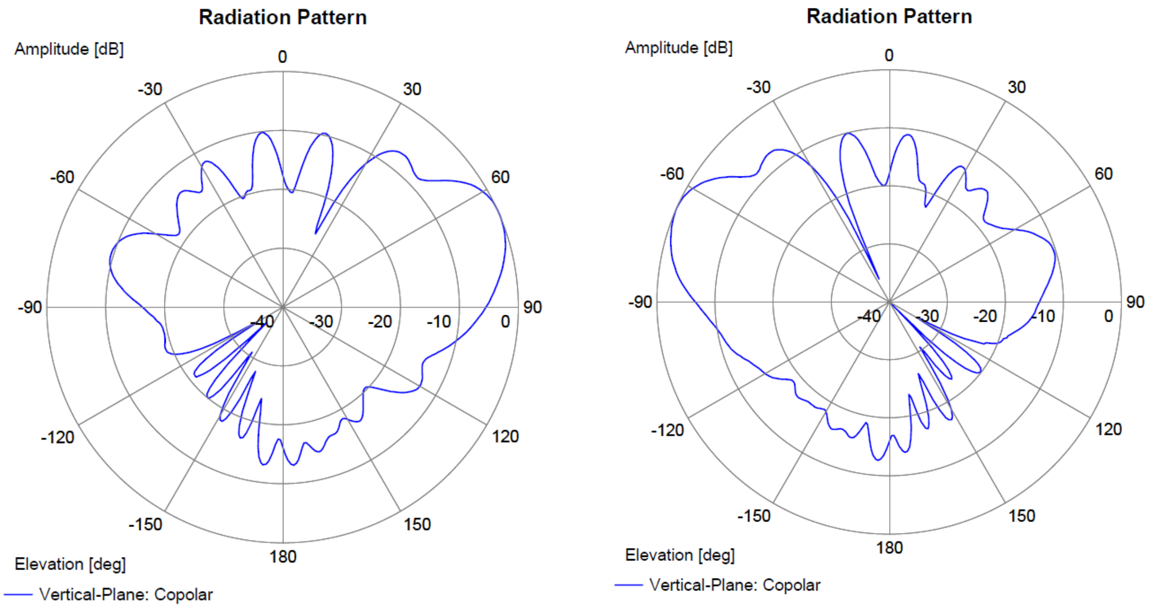


Figure 4-10: Vertical pattern @1855 MHz (H&S 1399.99.0130)

The example of the antenna pattern of the MIMO antenna shows quite well that the antenna might have a reasonable gain, but as in the mobile environment the main lobe of the train antenna element might not always direct towards the base station. This gain should not be considered in the coverage planning, especially assuming the presence of only one Tx antenna at the UE and the Uplink being the critical path.

For the reference configurations below, an antenna gain of 0 dBi seems to be reasonable.

4.2.5 On-board RF transmit level

For GSM-R network planning, the coverage level was defined as the received field strength at the antenna on the roof of a train (nominally a height of 4m above the track), thus downlink based. An isotropic antenna with a gain of 0 dBi has been assumed for that.

In FRMCS the Uplink is the limiting factor and within 5G rather than just a field strength, other metrics will be necessary in defining the coverage (e.g., SINR, RSRP, MCS as per chapter 3). FRMCS coverage planning therefore must consider the uplink. The parameter that includes all relevant constituents at the train side is the effective isotropic radiated power (EIRP) which is defined as:

EIRP = TX power(dBm) – cable loss(dB) – connector loss(dB) – filter loss(dB) + antenna gain(dBi)

4.3 Reference configuration and associated losses

As for FRMCS the uplink is the limiting factor, defining the minimum required EIRP on the train side would allow flexibility of the installations as shown with the following examples. For these examples the train antenna gain is assumed to be 0 dBi, with different losses between modem and antenna for cable losses, connector losses, plus a reserve for aging. The UE is assumed to be a PC1 UE.

Based on current experiences with GSM-R train configurations, Table 4-4 shows attainable EIRP levels. However, it is to be noted that the European spectrum regulation allows 33 dBm EIRP (31 dBm UE output power plus 5 dBi antenna gain minus 3 dB hardware losses). Further interaction with industry and FRMCS projects are ongoing with the goal to achieve an EIRP level as close as possible to the regulatory maximum allowed.

Both inputs from UNITEL, antenna and radio/modem industry and MORANE2 are expected to provide the necessary information on this.

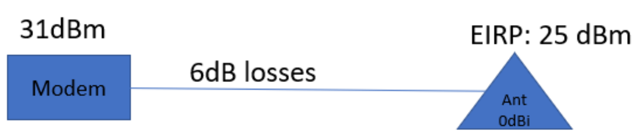
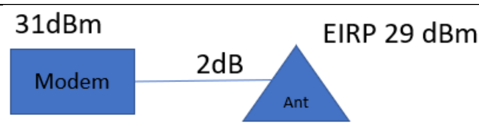
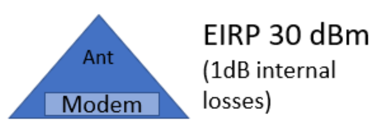
Configuration	Resulting EIRP	Comments
Integrated TOBA setup	 Note: 6dB losses are described in section 4.2.1.1	Worst case EIRP to allow centralized setup, PC1 UE needs to be available.
Distributed TOBA setup with remote radio function	 Note: 2dB losses are described in section 4.2.1.2	OB_{RAD} interface necessary for remote radio function
Integrated remote radio module + antenna		Open issues: Integration of filters. Thermal stability OB_{RAD} interface necessary

Table 4-4: TOBA Configuration and Resulting EIRP

This shows that the lowest EIRP that can be achieved with a PC1 UE in an integrated TOBA setup would be 25dBm.

5 Outlook

As an outlook, but depending on the available time and resources, additional topics and subjects will be further studied by UIC´s Group for Frequency Aspects. From today´s perspective the following topics regarding the FRMCS RAN for migration and beyond are of interest:

- Coexistence with adjacent services
  - Coexistence with bands adjacent to n100
  - Coexistence with bands adjacent to n101

- Infrastructure aspects
  - General RAN architecture aspects
  - 900 MHz <5 MHz CBW
  - 900 MHz Whitespace
  - Antennas

- Other RMR user equipment:
  - FRMCS handheld
  - MNO band radio module

- Cross-border aspects
  - RMR operator agreements/arrangement details
  - FRMCS coverage overlaps

- 5G technology options
  - Dual connectivity & Carrier aggregation
  - Other R19 WI / features
  - Beamforming
  - Other 5G features

- FRMCS – MNO hybrid
  - Minimum set of MNO bands (as optional for SRS v2)
  - FRMCS Multipath
  - RAN sharing/MOCN architecture
  - On-board antenna deployments and coexistence issues
  - Example of practical signal level for MNO usage

- FRMCS Field trial needs and results

- Track certification for packet transmission and coverage measurements

Annex 1 List of references

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2. ECC Decision (20)02
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4. Kontron Test Report : Whitespace Solution Concept for GSM-R and LTE Coexistence Scheme: Tests Results
5. FRMCS radio network planning issues KT20220128
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